# Progress on the European Extremely Large Telescope

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**In December 2006 the ESO Council gave the go-ahead for the European Extremely Large Telescope (E-ELT) three-year Phase B study. The Baseline Reference Design (BRD) was presented to the ESO committees in 2006 and to the community at the Marseille meeting in December 2006. Phase B has been running for one and a half years and a progress report is presented covering science activities, telescope design, instrumentation, site selection and operations. The designs are maturing, in close synergy with industrial contracts, and the proposal for E-ELT construction is expected to be presented to the ESO Council in June 2010.**

The decision by the ESO Council to fund the Phase B for the E-ELT at their meeting in December 2006, and the adopted baseline telescope design, were described in Gilmozzi & Spyromilio (2007). The meeting "Towards the European Extremely Large Telescope", which was held in Marseille immediately preceding the Council decision, was reported in the same issue of the Messenger (Hook, 2007; Monnet, 2007; Cuby, 2007). Now one and a half years later there has been much progress as well as evolution of the design of the telescope.

## Science activities

Science activities for the E-ELT Phase B have now ramped up to full speed. Besides focussing on the Design Reference Mission (DRM), a small science office, under the guidance of and in close collaboration with the Science Working Group, is developing a Design Reference Science Plan (DRSP) and consolidating the top level requirements for the observatory. These activities are supported by the EU FP7 sponsored programme which has been funded (see Gilmozzi et al., 2008). Details about the science case, the science working group activities and the DRM can be found at *http://www.eso.org/sci/facilities/eelt/science*. A brief synopsis is given below.

The basic idea of the DRM is to be able to predict and monitor the ability of the telescope to effectively and efficiently address the challenges of the science cases. For this purpose, a number of key science cases proposed by the Science Working Group are being simulated in detail (see also Hook, 2007). For most science cases, simulations address key results to be achieved as a function telescope and instrument parameters. In some cases, the simulations will be performed end-to-end in order to provide additional feedback to the operations models.

A large amount of technical data is required for the simulations (such as atmospheric behaviour, telescope parameters and instrument models, as well as simulated adaptive optics point spread functions), and is made available to the public on the web pages under "Technical data for simulations" *(http://www.eso.org/sci/facilities/eelt/science/drm/tech_data/)*. A workshop was held in Garching on 20 and 21 May bringing together a number of the astronomers engaged in simulations for the DRM and/or instrument concept studies. The programme and presentations of this workshop can be found at *http://www.eso.org/sci/facilities/eelt/science/drm/workshop08/programme.html*.

While the DRM provides a detailed insight into the expected performance of the E-ELT, the DRSP is intended to explore the parameter space to be covered by the telescope and instruments. The DRSP will be a large collection of cases directly provided by the ESO community, and reflecting their interests. A web questionnaire is being made available from September 2008 on. This collection of cases will be analysed and will be used as one of the drivers for the telescope modes and instrument implementation plans.

Beyond the work on the science case, the E-ELT science office is currently consolidating the top level requirements for the observatory. Telescope and instrument requirements are being reviewed and justified in order to provide the necessary background for the decisions on the trade-offs to be made during the detailed design work on the telescope.

A number of workshops will be held in the near future to discuss the E-ELT science cases. In September, during the JENAM meeting in Vienna, there will be a major workshop "Science with the E-ELT" (see *http://www.eso.org/sci/facilities/eelt/science/meetings/jenam08/*). Two workshops are being prepared for next year. The first, in March 2009, is organised together with the ALMA, GMT and TMT projects (see announcement on page 65). The aim is to explore the synergies between ALMA and the up-coming giant optical and near-infrared telescopes. The second workshop (May 2009) will be dedicated to the DRM and DRSP work in the frame of the FP7 activities.

## Telescope design

The design activities undertaken by industry as part of the Phase B, and their impact of the current version of the BRD, are described in the following sections. One significant evolution of the five-mirror design (see Gilmozzi & Spyromilio, 2007) has been the movement of the tertiary mirror from below the primary mirror to the same level. This change was made to improve the ventilation of the tertiary mirror. As a by-product the secondary mirror has become slightly smaller in diameter (now 6 m rather than 6.2 m). The adaptive quaternary mirror has increased slightly in diameter, thereby marginally improving its performance.

## Industrial activities

Immediately after the approval by the ESO Council, a set of contracts were tendered to validate the BRD for the telescope and to explore the expertise in industry regarding the construction of such massive structures. The general policy has been to let two contracts to study a specific subsystem of the telescope, thus allowing different options to be explored whenever possible.

By May 2007 two contracts had been placed for the validation of the telescope main structure design as proposed by

ESO. The contracts included the study of the industrialisation of the concept, cost estimates and construction schedules. We encouraged the suppliers to consider variations on the design. Both these design contracts have now been concluded. The contractors considered variants on the ESO baseline and proposed alternatives that appear to perform better and are estimated to be cheaper to manufacture. The ESO design team has adopted these ideas and the new baseline telescope main structure appears significantly different to the original concept (see Gilmozzi & Spyromilio, 2007). Instead of four cradles supporting the primary mirror, only two are now seen as necessary to provide the required stiffness. By removing a significant fraction of the mass from below the telescope, the mount balances naturally, alleviating the necessity of significant additional mass in the upper parts of the telescope (see Figure 1). This change has increased the overall performance of the telescope and the first eigenfrequency of the structure is now around 2.6 Hz. The reduction in moving mass is also an overall cost saver, both in quantity of steel and in all the associated hardware.

The design for the telescope mount has been extensively analysed using Finite Element Models and fairly sophisticated control simulations (see Figure 2). Although the role of the mount may be simplified to "Keep the primary pointing at the right place on the sky, and the other mirrors at each other (sequentially)", not only is this a non-trivial problem but the optimisation of the design can lead to significant cost savings in other subsystems. For example, the range of the actuators for the primary mirror is directly related to the extent to which the cell will deform as the telescope is inclined from the zenith towards the horizon.

Around the same time as the call for contracts for the telescope main structure, two contracts were placed for a preliminary design of the telescope dome. The companies that provided the best bids in response to the ESO tenders were new to telescope enclosure design, but brought their expertise in the design and construction of enormous buildings, and in particular sports stadia, to bear. The E-ELT dome will be of similar size to that of

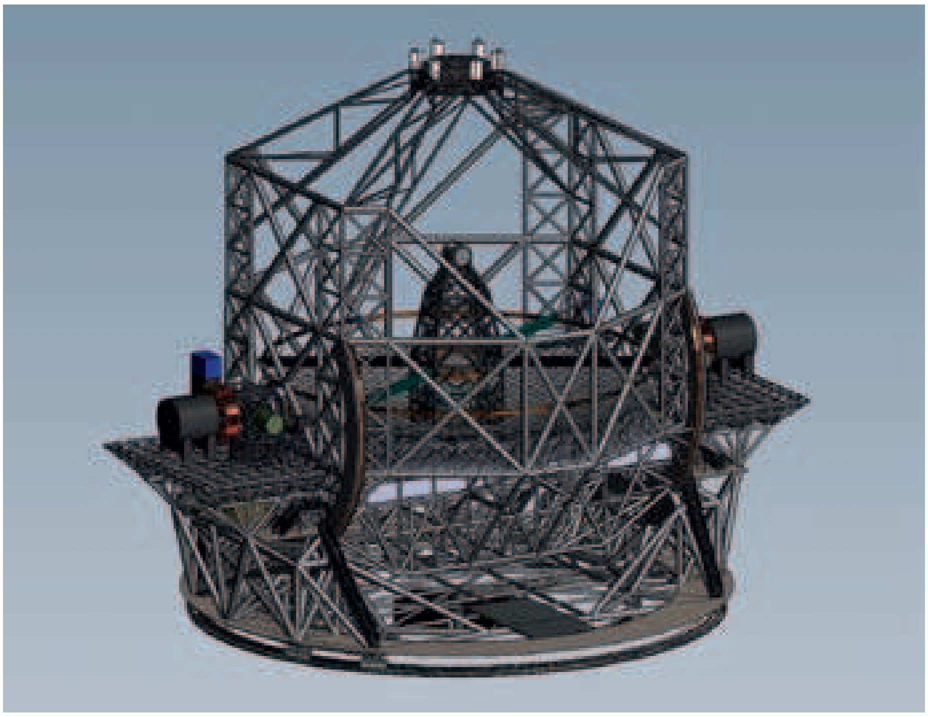
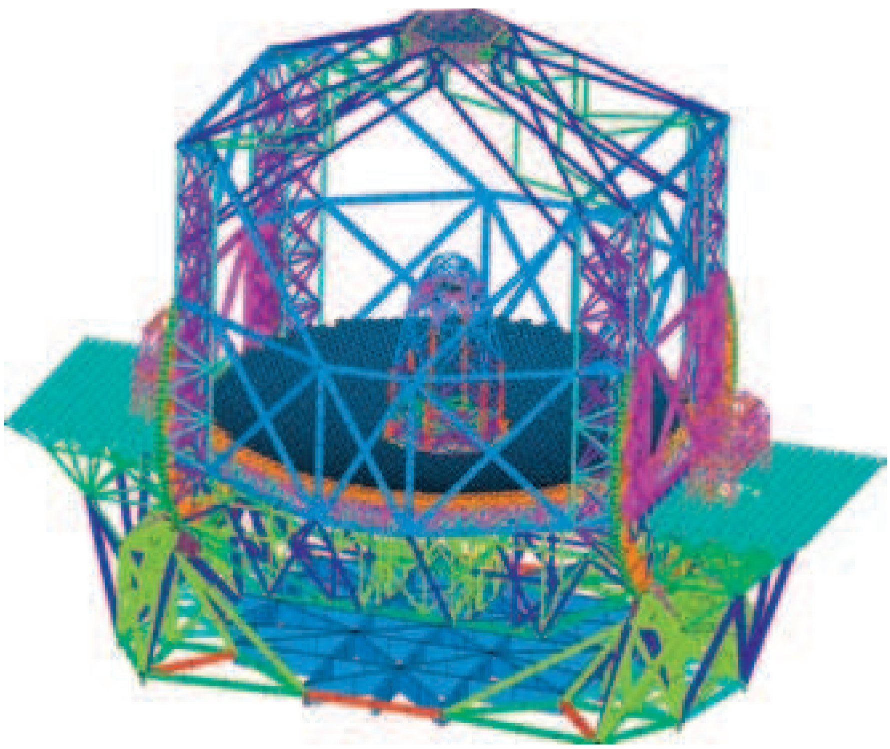


Figure 1 (above). A CAD rendering of the E-ELT Baseline Reference Design version 2 for the telescope and mount.

Figure 2 (below). A Finite Element Model of the E-ELT main structure is shown. The different coloured components encode different cross sections of the structural elements.



a football stadium, with a diameter at its base of order 100 m and a height of order 80 m. These contracts were particularly interesting to follow as the industrial expertise in this area is extensive, but also the requirements of a telescope dome are sometimes quite peculiar. Of the many challenges faced during the design of the dome, two stand out as having required ingenious solutions: the wind screen that shields the telescope from the effects of the wind; and the twenty-tonne crane that can access the entire volume of the dome. We are pleased to say that both designs proposed have elegant solutions for these two aspects. The two designs are similar to the extent that both assume a hemispherical dome but quite different in how the dome is supported and in the nature of the observing doors. One design proposes a single pair of large doors (see the image on the front cover), while the other proposes two sets of nested doors. Both suppliers have provided schedules for construction and the estimated costs for the dome. Figure 3 shows a cross-section through one of the E-ELT dome designs.

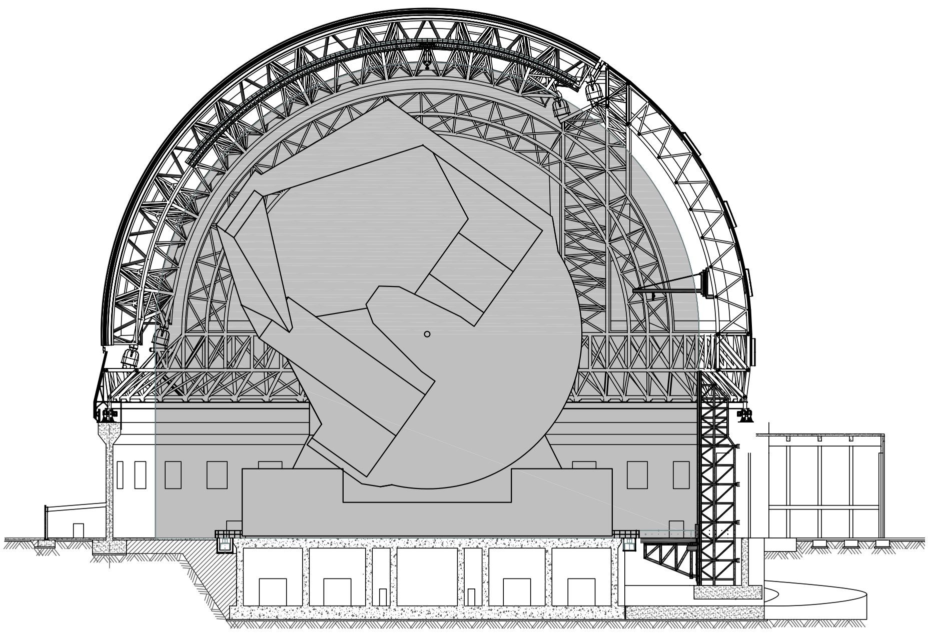


Figure 3 (above). A diametral cross section of one of the two concepts developed for the E-ELT dome.

Extensive investigation is being undertaken in the area of the impact of the wind on the telescope and the effect of the dome. Wind tunnel measurements have already started, computational fluid dynamical (CFD) simulations are ongoing and a campaign of fast sonic anemometer measurements was undertaken at Paranal.

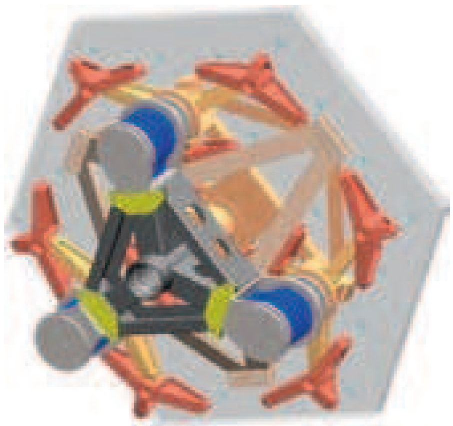


Figure 4 (left). A CAD figure of one of the mirror segment assemblies. The segment is shown on the 27 point wiffle tree; the three blue cylinders are the actuators for tip-tilt control.

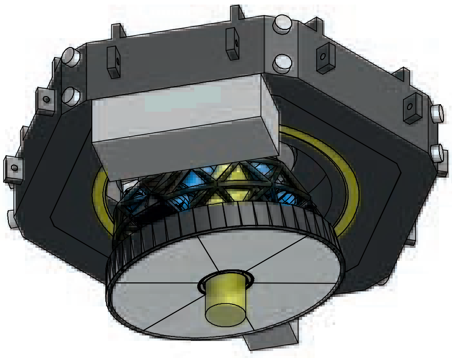
A contract was placed in mid-2007 for the design of the primary mirror cell and the supporting elements. The support of the 984 1.45-m hexagonal mirror segments that form the primary mirror of the telescope is a critical component of the telescope design. The 50-mm thickness of the mirror segments is necessary to reduce the weight of the mirror. However, the thin segments are susceptible to deformation due to imperfections in their supports and the print-through of these supports onto the reflecting surface, which could limit the performance of the telescope. The mirror cell contractor analysed two types of support, one with 27 points and one with 18. The supporting principle is that the axial loads (i.e. in the direction through the segment) are taken with a wiffle tree structure, while the lateral loads are taken by a membrane implanted in the centre of the segment. The concept for the support structure has evolved significantly from the BRD. A moving frame carries the wiffle tree and the central membrane. The moving frame is moved in piston and tip-tilt by three actuators (see Figure 4). Additionally six motorised warping harnesses are foreseen to allow for the necessary corrections to the segment shape. A further restraint is designed to limit the clocking (i.e. rotation in the plane of the segment). The side of the segment not facing the sky is likely to be very complex as Figure 4 implies. The contract for the design has been concluded with ESO selecting the 27-point over the 18-point support. While the latter fulfilled the requirements for the extreme performance of the telescope, the former provided for a small but significant margin. In addition to the design of the segment support, we have also been testing the prototype edge sensors in a climatic chamber and continue to explore the actuator market.

In the third quarter of 2007, three large contracts for the adaptive optics system of the telescope were placed. Two of the contracts were for a preliminary design and prototyping of the adaptive quaternary mirror (M4; see Figure 5) and the third was for the design and 1:1 scale prototype of the electro-mechanical unit to support the fifth tip-tilt mirror (M5; see Figure 6) in the telescope optical train. All three contracts have gone through the first preliminary design phase (Figures 5 and 6) and there is great interest in the prototyping activities. Real hardware is being built for these prototypes, including some very sophisticated actuators employing some of the biggest piezo-stacks currently available, tests of cooling circuits, etc. While the prime contractors leading the activities are well known companies in their areas of expertise, it is very reassuring that they have engaged other companies with differing expertise, such as in the areas of optics and/or complex opto-mechanical systems, to form powerful teams demonstrably able to address the challenges of the adaptive optics for the E-ELT.

Two further large contracts were placed in late 2007. They entail the production of seven prototype segments for the primary mirror of the telescope. While seven segments, out of the 1148 that will need to be produced, may not sound very many, the contractors are required to demonstrate the industrialisation of the production process and test their mass production techniques on a variety of mirror substrates. Here again real hardware is being prepared for the manufacturing of the mirror segments. A new big polishing machine is under manufacture for the 1.45-m segments and the design of the test set-up used to determine the performance of the polishing is well advanced.

In May 2008 a further significant contract was placed for the design study of the secondary mirror cell. The tendering process is already progressing well for the tertiary mirror cell and the pre-focal unit (adapter/rotator and M6 housing; see Figure 7). It is expected that contracts with industrial firms will be placed by the end of this year. A significant amount of work has been undertaken at ESO to understand the wavefront sensing needs of the telescope and to develop strategies for phasing the primary mirror, distributing the aberrations amongst the various mirrors, sensing lasers and natural guide stars. The progress has been significant and modern systems engineering processes and modelling languages have been employed to help.

One significant modification, relative to the BRD version 1, in the area of the



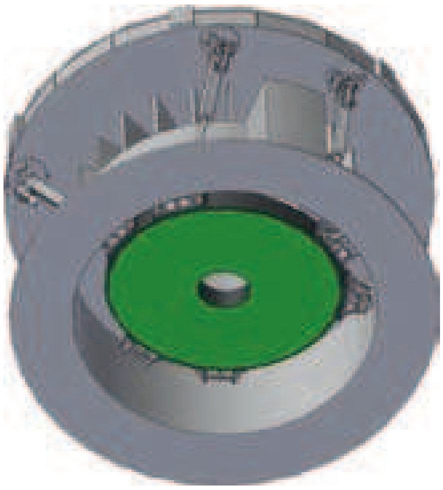


**Figure 5 (above and right).** Two preliminary designs for the M4 deformable mirror unit.

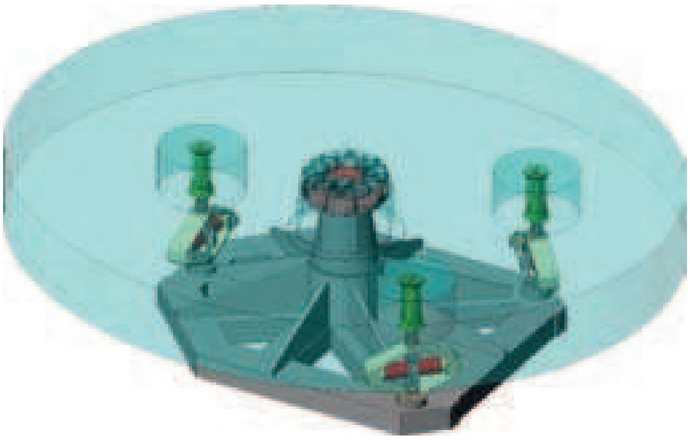
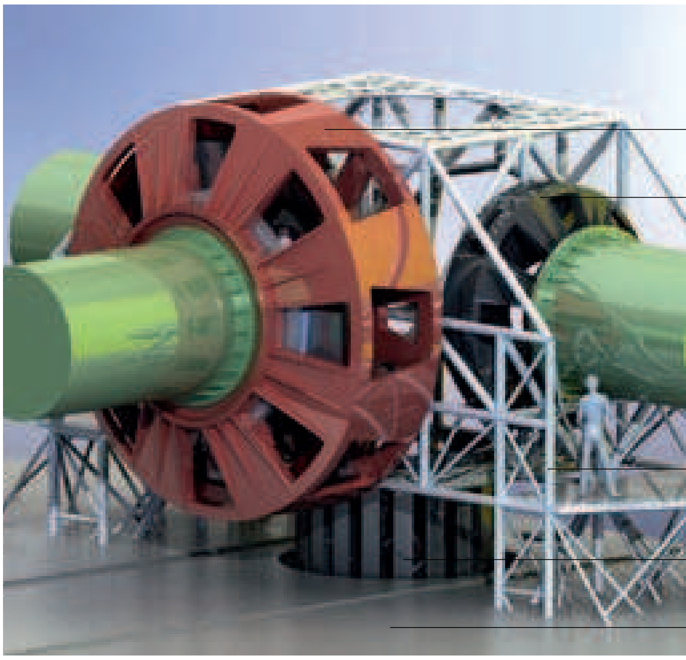


**Figure 6 (left).** The prototype design of the tip-tilt M5 mirror unit.

**Figure 7 (below).** CAD rendering of a Nasmyth platform populated with indicative instrument volumes and the prefocal unit.



adaptive optics instrumentation has been the merger of the two adapters at each Nasmyth focus into a single unit, and the reduction of the number of lasers necessary for the Ground Layer Adaptive Optics (GLAO) mode of the telescope from six to four (see Figure 8). The telescope will in any case be equipped with more than four lasers for the benefit of Laser Tomography Adaptive Optics (LTAO) and Multi-Conjugate Adaptive Optics (MCAO) instruments.

The effort in integrated modelling undertaken under the auspices of the FP6 study (see next section) has been further funded by the telescope project office. It is expected that great insight into the project will come through such efforts. Additionally many smaller, but no less significant, investigations are ongoing in areas such as the coating chambers for the mirrors, mirror segment replacement, general handling issues, etc. A detailed manpower estimate for technical operations is currently under review.

## Activities undertaken within the FP6 ELT Design Study

There has been good progress in the areas of study funded through the broad consortium of institutes and industrial partners within the EU FP6 ELT Design Study programme (see Gilmozzi & Spyromilio, 2007). The edge sensor work is providing excellent results. Testing of the inductive edge sensors in a climatic chamber is being undertaken and they are performing remarkably well. The actuators which have been developed are being produced for the Wind Evaluation Breadboard of the primary mirror segments, an activity that will begin at the end of the year.

## Consolidation of the Phase B activities

With so many industrial studies continuing in parallel and together with the in-house work on a broad range of topics from interfaces, error budgets, alignment strategies, presetting sequences to mirror phasing plans and primary mirror segment exchanges, the project has established milestones that allow it to re-baseline the design in response to these inputs. The transition from BRD version 1 (i.e. that presented to the ESO Council and the committees and community at the end of 2006) to BRD version 2 took place at the end of February 2008.

The process of bringing together all the inputs generated a series of open issues that are being addressed in what we refer to as the ‘consolidation phase’. We are progressing rapidly towards the baseline BRD version 3 that we expect to achieve by the end of this year. As the project advances we are also accreting more people from within ESO to work on various activities. Figure 9 shows the members of the team present at our BRD version 2 review, held in spring 2008.

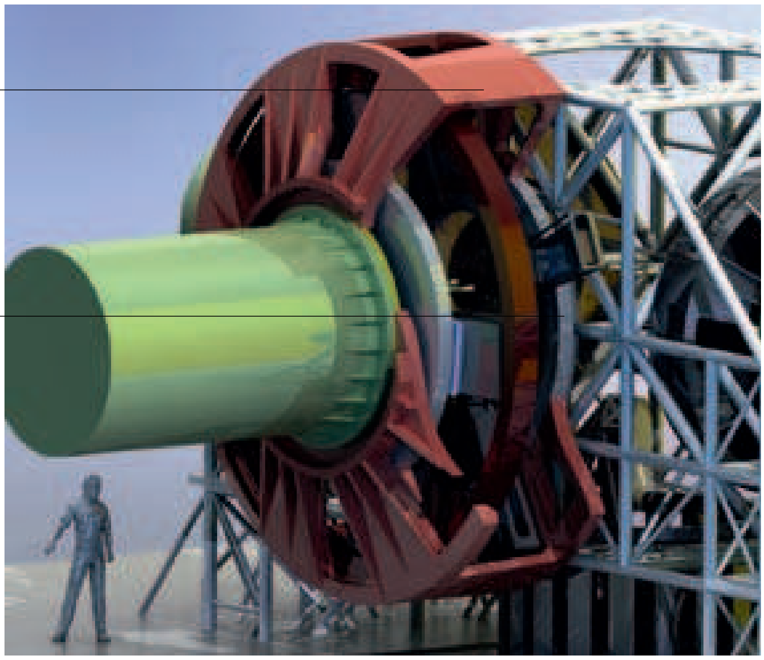



Figure 8 (above). Detail of the CAD model for the adaptor rotator housing for the Nasmyth focus showing the laser and natural guide star units.

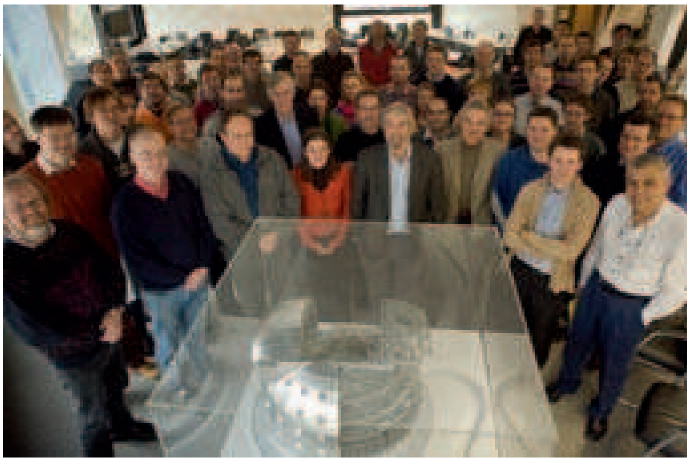


Photo: H. H. Heyer, ESO

Figure 9. The ESO E-ELT team, arrayed behind a model of the E-ELT dome, during the Baseline Reference Design meeting held from 29 February to 4 March 2008 at ESO Headquarters.

## Instrumentation

The E-ELT programme requires an early start on the instrumentation studies in order to confirm the scientific capabilities of the telescope, to identify those subsystems that need more research and development and to prove the feasibility of the instruments at an affordable cost and within the project schedule. In addition, the instrumentation studies at this phase of the project provide very useful feedback to the telescope design and the observatory infrastructure. An E-ELT Instrumentation Project Office has been established to work on the instrument studies and the telescope interface. A plan for instrument and post-focal adap-

Table 1. Instrument and AO Module Studies (as of August 2008).

| Name | Instrument Type | Principal Investigator<br>Institutes |
|---|---|---|
| EAGLE | Wide Field, Multi IFU NIR Spectrograph with MOAO | Jean-Gabriel Cuby, Laboratoire d'Astrophysique de Marseille (LAM);<br>Observatoire Paris-Meudon (OPM), Laboratoire d'Etudes des Galaxies, Etoiles, Physique et Instrumentation (GEPI) and Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA); Office National d'Etudes et Recherches Aérospatiale (ONERA); United Kingdom Astronomy Technology Centre (UK ATC); Durham University, Centre for Advanced Instrumentation |
| CODEX | High Resolution, High Stability Visual Spectrograph | Luca Pasquini, ESO;<br>Istituto Nazionale di Astrofisica (INAF), Osservatori Trieste and Brera; Instituto de Astrofísica de Canarias (IAC); Institute of Astronomy, University of Cambridge; Observatoire Astronomique de l'Université de Genève |
| MICADO | Diffraction-limited NIR Camera | Reinhard Genzel, Max-Planck Institute for Extraterrestrial Physics (MPE);<br>Max-Planck Institute for Astronomy (MPIA); INAF, Osservatorio Padova; Nederlandse Onderzoekschool Voor Astronomie (NOVA), Universities of Leiden and Groningen |
| EPICS | Planet Imager and Spectrograph with Extreme Adaptive Optics | Markus Kasper, ESO;<br>Laboratoire d'Astrophysique de l'Observatoire de Grenoble (LAOG); LESIA; Université de Nice; LAM; ONERA; University of Oxford; INAF, Osservatorio Padova; ETH Zürich; NOVA, Universities of Amsterdam and Utrecht |
| HARMONI | Single Field, Wide Band Spectrograph | Niranjan Thatte, University of Oxford;<br>Centre de Recherche Astrophysique, Lyon; Departamento de Astrofísica Molecular e Infraroja, Consejo Superior de Investigaciones Científicas, Madrid; IAC; UK ATC |
| METIS | Mid-infrared Imager and Spectrograph with AO | Bernhard Brandl, NOVA, University of Leiden;<br>MPIA; Commissariat à l'Energie Atomique (CEA) Saclay, Direction des Sciences de la Matière (DSM)/Institut de Recherches sur les lois Fondamentales de l'Univers (IRFU)/Service d'Astrophysique (SAp); Katholieke Universiteit Leuven; UK ATC |
| OPTIMOS | Wide Field Visual MOS | tbd<br>Negotiations under way with a Consortium of Science and Technology Facilities Council, Rutherford Appleton Laboratory; University of Oxford; LAM; INAF, Istituto di Astrofisica Spaziale e Fisica Cosmica, Milan; GEPI; NOVA, University of Amsterdam; INAF, Osservatori Trieste and Brera; Niels Bohr Institute, University of Copenhagen |
| SIMPLE | High Spectral Resolution NIR Spectrograph | Livia Origlia, INAF, Osservatorio Bologna;<br>INAF, Osservatorio Arcetri; INAF, Osservatorio Roma; Uppsala Astronomical Observatory; Thüringer Landessternwarte; Pontificia Universidad Católica de Chile |
| MAORY | Multi Conjugate AO module | Emiliano Diolaiti, INAF, Osservatorio Bologna;<br>INAF, Osservatorio Arcetri; INAF, Osservatorio Padua; University of Bologna; ONERA |
| tbd | Laser Tomography AO Module | Thierry Fusco, ONERA;<br>GEPI and LESIA |

tive optics studies, to be carried out in collaboration with institutes in the ESO community, was presented to the ESO Council in June 2007. The plan identified six instrument concepts, two post-focal AO modules (MCAO and LTAO) of high priority and two other instruments to be chosen after an open call to the community for additional concepts. By September 2008, all ten instrument consortia have been formed and the studies are under way (see Table 1). In two cases the consortia are led by ESO, two have been set up with a direct negotiation with external institutes and all the others have been selected after an open Call for Proposals. In this study phase, the instrumentation activities are supported by 2.4 Million Euros (of which ~ 85 % is committed to support external institutes involved in the studies) and 30 ESO FTEs. On the community side, 36 institutes in 10 ESO member states and one in Chile are contributing to the studies as part of the 10 consortia, with a combined effort over two years of more than one hundred FTEs.

All the studies are structured in two phases. During the first, the scientific requirements are defined and a trade-off between different concepts is made. After a review of the results by ESO, in the second phase a detailed study of the chosen concepts, including cost and construction schedule, is carried out. All studies are expected to deliver a report and to go through a final review in late 2009 or early 2010.

On the basis of these studies, ESO will include in the E-ELT proposal for construction an outline of the first generation of instruments and a plan on how to proceed with their construction. In parallel to launching these studies, the opto-mechanical interfaces with the telescope have been defined and incorporated in a document that has been made available to the instrument consortia (see Figure 10). As the studies of the telescope subsystems are taking place in parallel with those of the instruments, very useful exchanges are continuing to take place during this phase between the telescope and instrument teams to arrive at a common set of requirements.

## Site selection

Several sites, both in the Northern and Southern hemispheres, are being characterised, in large part with the help of the community through the FP6 initiative. A Site Selection Advisory Committee has been appointed by the Director General to help ESO towards a decision. It is foreseen that site selection will occur at the end of 2009.

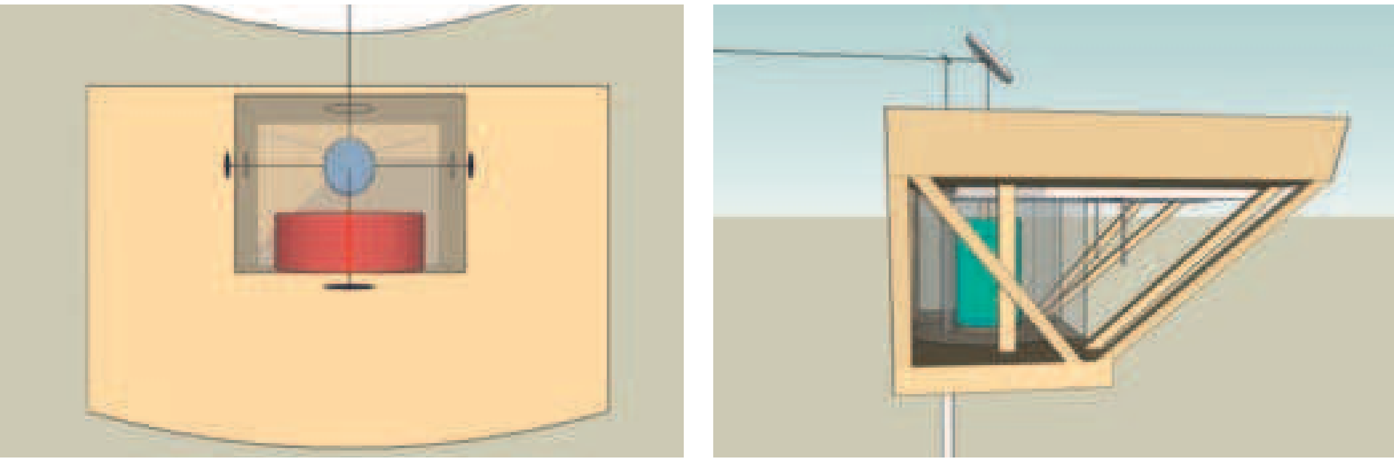


Figure 10. Figures taken from the E-ELT telescope interface document distributed to the instrument consortia, showing the layout of the Nasmyth platform with its four focal stations. **Left:** View from above (the dimensions of the platform are 24 by 15 m). **Right:** Side view showing the volume reserved for an instrument in the gravity-invariant focal station below the floor of the platform. This space is intended for large instruments that have to rotate during observations.

## Operations

The science operations planning that is being developed during Phase B takes as a basis the current end-to-end model of the VLT, since the scientific requirements are similar to those currently encountered at the VLT. Specifically, as reflected in the DRM, the E-ELT will have to be able to execute a broad range of programmes using a variety of instruments and modes, many of them requiring performance of the telescope and instruments that can be achieved only under rare atmospheric conditions. The flexibility to schedule at short notice those programmes that can make best use of the prevailing conditions is thus a requirement for the efficient use of the facility.

The E-ELT design permits such flexibility. Several instruments, able to exploit different ranges of atmospheric conditions, will be either online or on standby at any given time. As specified in the top-level requirements and the telescope design, it will be possible to switch from one instrument to another with a moderate overhead of a few minutes, including the set-up of the post-focal adaptive optics module if needed. The telescope and dome will be able to preset from any position of the sky to any other, acquire the target field, and close the telescope adaptive optics loop on a similar timescale.

Service mode without real-time interaction between the users and the facility provides the greatest level of flexibility and is taken as the baseline observing mode for the E-ELT. However, it is anticipated that a fraction of programmes will require real-time interaction, allowing users to make decisions in the course of the observations at short notice. We expect to better quantify the fraction of time that the E-ELT will spend executing such classes of programmes as a result of the DRSP questionnaire described earlier. To satisfy this requirement, we are studying the implementation of new observing modes that allow users to interact with the facility in near-real time without being present in the control room, while retaining much of the scheduling flexibility necessary for the proper exploitation of the atmospheric conditions. Some specific implementation aspects of these modes have been studied in the FP6 activities on observatory operations.

We have produced estimates of the typical and peak data rates expected from each instrument based on their Phase A study specifications, in order to quantify the capabilities needed from the communications infrastructure between the observatory and the outside. E-ELT operations planning assumes that support to science operations will be provided by geographically distributed groups, who will be exchanging data on a short timescale over fast data distribution channels.

Preliminary estimates of the science operations staffing needs, in terms of number and qualifications, have been produced. The estimate is based on factors such as the breakdown of tasks to be carried out in end-to-end operations, the complexity of the systems being operated, the personnel working schedule, the location of each operations group, and the synergies with the operation of other facilities. It may be noted in this regard that significant cost savings in operations are achieved by having operations groups sharing the E-ELT support tasks and infrastructure with the support to other ESO facilities, particularly in the areas of user support, data processing, and archive operations.

## Prospect

The E-ELT Phase B was funded for 57.2 Million Euro, including manpower. The majority of these funds have already been committed and technically the project is advancing well. We are on schedule to produce the construction proposal in time for the June 2010 ESO Council meeting.

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