Recent Progress Towards the European Extremely Large Telescope (E-ELT)

Alistair McPherson[1]
Roberto Gilmozzi[1]
Jason Spyromilio[1]
Markus Kissler-Patig[1]
Suzanne Ramsay[1]

[1] ESO

ESO contributors to this work include:
Jose Antonio Abad, Luigi Andolfato, Robin Arsenault, Joana Ascenso, Pablo Barriga, Bertrand Bauvir, Henri Bonnet, Martin Brinkmann, Enzo Brunetto, Mark Casali, Marc Cayrel, Gianluca Chiozzi, Richard Clare, Fernando Comerón, Laura Comendador Frutos, Ralf Conzelmann, Bernard Delabre, Alain Delorme, Canio Dichirico, Philippe Dierickx, Martin Dimmler, Mark Downing, Toomas Erm, Michael Esselborn, Robert Frahm, Christoph Frank, Enrico Fedrigo, Giorgio Filippi, Peet Fourie, Fernando Gago, Paolo Ghiretti, Frederic Gonte, Juan-Carlos Gonzales, Serge Guniat, Carlos Guirao, Stephane Guisard, Juan-Pablo Haddad, Wolfgang Hackenberg, Volker Heinz, Renate Hinterschuster, Ronald Holzlöhner, Richard Hook, Norbert Hubin, Lisselotte Jochum, Andreas Jost, Noé Kains, Dimitrios Kalaitzoglou, Robert Karban, Markus Kasper, Hans-Ulrich Käufl, Lothar Kern, Mario Kiekebusch, Franz Koch, Bertrand Koehler, Johann Kolb, Nick Kornweibel, Maximilian Kraus, Paolo La Penna, Miska LeLouarn, Samuel Lévêque, Stefan Lewis, Jochen Liske, Jean-Louis Lizon, Gianluca Lombardi, Antonio Longinotti, Fernando Luco, Christian Lucuix, Pierre-Yves Madec, Enrico Marchetti, Juan Marrero, Javier Marti, Jorge Melnick, Katia Montironi, Christian Muckle, Michael Mueller, Julio Navarette, Helène Neuville, Lothar Noethe, Paolo Padovani, Luca Pasquini, Jérôme Paufique, Lorenzo Pettazzi, Marco Quattri, Jutta Quentin, Andrea Richichi, Robert Ridings, Mark Robinson, Michael Rosa, Stefan Sandrock, Pierre Sansgasset, Marc Sarazin, Michael Schneermann, Dominik Schneller, Babak Sedghi, Ralf Siebenmorgen, Isabelle Surdej, Arek Swat, Donald Tait, Roberto Tamai, Arno van Kesteren, Elise Vernet, Joël Vernet, Gianluca Verzichelli, Anders Wallander, Yves Wesse, Natalia Yaitskova, Michele Zamparelli.

The European Extremely Large Telescope (E-ELT) has evolved over the last few years since the phase B review of the 42-metre design. While the design was strongly endorsed, the cost exceeded the maximum envelope and a re-baselining was implemented by the Project Office. The extent and ramifications of the new design are outlined including scientific, engineering and managerial aspects. Prototyping activities of some of the components are described and the first light instruments have been selected. The new baseline for the 39-metre E-ELT has been accepted by the ESO Council and awaits the decision on the start of construction.

The European Extremely Large Telescope (E-ELT) design has evolved significantly since the last report in *The Messenger* (Spyromilio et al., 2008) and here we aim to update the community on the activities within the E-ELT Project Office during the past few years. The construction proposal prepared for the ESO Council has been widely publicised and is available on the ESO website[1].

In the second half of 2010, the E-ELT programme underwent a series of technical and managerial reviews that provided a strong endorsement of the construction project. The activities undertaken during the phase B (2007–2010) were thoroughly reviewed by a board of external experts in September 2010 (see Kissler-Patig, 2010). The executive summary of the board report has been available for some time[2]. The short version is that "it [was] the unanimous conclusion of the review board that the technical maturity of the design of the E-ELT was sufficient to warrant the programme entering the construction phase". Moreover, the "E-ELT budget was highly cost-effective" and the "FEED methodology had been highly effective in generating reliable cost estimates" (for a definition of FEED see below p. 8).

However, the final cost estimate at the end of phase B was € 200 million above the top end of the target. The project was asked to consider whether any significant cost savings could be delivered without compromising the scientific capabilities of the telescope. Unfortunately the answer to this question was no. Some reduction in scope from the 42-metre aperture would be necessary. On the other hand, following a four-year design development phase the project was also aware of areas where technical and programmatic risks existed. Realistic funding scenarios gave an earliest possible start for the project in 2012 and therefore there was time to work on mitigating those risks. The Project Office undertook to explore cost saving and risk mitigation options during 2011. These changes have been adopted by the ESO Council as the baseline for the new 39-metre E-ELT.

Science capabilities

A primary concern with respect to the new baseline for the telescope was its impact on the scientific capabilities. The E-ELT Science Office, together with the Science Working Group studied the impact on the science of the various modifications to the baseline design using the Design Reference Mission[3] and Design Reference Science Cases[4] as benchmarks for the evaluation.

The diameter of the primary mirror is the most fundamental and most important characteristic of any telescope system, but particularly for an adaptive optics assisted telescope, as it determines both its diffraction-limited spatial resolution as well as its photon-collecting power. These properties may combine differently depending on the scientific goal, as well as the observational and astrophysical circumstances. The result is that there can be many different ways in which a given science case may depend on the diameter.

At the highest level we may distinguish between the following three classes of science cases: (i) cases where science is irretrievably lost by reducing the telescope diameter; (ii) cases where the loss of telescope diameter can be compensated for by increasing the observing time or adjusting some other observational parameter; (iii) cases that are not affected by the reduction of the telescope diameter at all.

The unique spatial resolution of the E-ELT is one of its defining characteristics and hence it is not surprising that many of the science cases that have been proposed for the E-ELT aim to exploit this feature. All cases that require the E-ELT resolution to disentangle their targets from other nearby sources will be forced to adopt less demanding goals for the 39-metre E-ELT than originally envisaged for the 42-metre design. This observational scenario encompasses a vast range of science cases, and prominent examples include the direct detection of exoplanets (all high-contrast imaging applications depend particularly strongly on the diameter), the study of the resolved stellar populations of other galaxies, and studies of supermassive black holes and their environments in the centre of our own and other galaxies.

The other subcategory in this class of irretrievable loss contains cases where the observing time cannot arbitrarily be extended, even in principle. Among such cases are included observations of non-recurring transient events, such as gamma-ray bursts (GRBs) or supernovae, and short recurring events with very long periods between repetitions, such as some eclipses or transits. In all of these cases the reduction of diameter will lead to a loss of signal-to-noise (S/N) that cannot be compensated for by increasing the integration time.

The second class of science cases contains those that are limited by the S/N that is achievable on their targets, and where the S/N is not dominated by (diameter-independent) astrophysical error sources or systematic uncertainties (astrophysical, instrumental, or otherwise). To a large extent these cases principally exploit the other key characteristic of the E-ELT, namely its unique photon-collecting power. The feature that is common to all of these cases, and which sets them apart from those in the first class, is that a decrease in diameter can be compensated for by increasing the observing time in order to achieve the same result with the 39-metre as with the 42-metre E-ELT. Again, this class encompasses a vast range of science cases. Prominent examples include most studies of high-redshift galaxies, investigations of the stellar populations in the Galaxy and the search for possible variations of the fundamental physical constants.

Finally, the third class of science cases contains those cases that are limited by (diameter-independent) astrophysical error sources or systematic uncertainties, or where the reduction of diameter can be compensated for by adjusting parameters that have essentially no impact on the science. We stress that we are only referring to cases that are quasi-independent of diameter for the specific regime under consideration here, i.e. when going from the 42-metre to the 39-metre aperture. This class does not encompass many cases, but one prominent example is the detection of low-mass exoplanets using the radial velocity method.

The overall loss of scientific efficiency resulting from the reduction of the E-ELT diameter depends of course on how the observing time will be distributed among the various science cases, each following different scaling laws. This is difficult to know *a priori*, but it is reasonable to assume that the E-ELT will spend much of its time doing science that depends on the power of the diameter to the squared or fourth power, resulting in an overall loss of efficiency in the range of 20 to 35%.

In addition to assessing the overall loss of scientific efficiency, it was also evaluated whether any individual science cases are rendered completely infeasible by the reduction in the E-ELT diameter, in the sense that the diameter is now below some critical threshold value for these cases. To summarise the result of this analysis: of all the major science cases for the E-ELT, the one that is most severely affected by the reduction of the telescope diameter is the direct imaging of Earth-analogue exoplanets. Nevertheless, the overall conclusion is that none of the major science cases for the E-ELT must be completely abandoned, and that, on the whole, the E-ELT science case remains intact and does not require any major revision.

The new telescope

The costs of the E-ELT are roughly divided between: 40% for the dome and main structure; 40% for the opto-mechanics; 10% for the instrumentation; and 10% for the rest. From this breakdown it should be obvious that no individual component would deliver the significant cost saving necessary to bring the telescope within the required cost envelope.

The natural choice of reducing everything but the telescope diameter could not work. Reducing the cost of the dome required a reduction in the overall volume occupied by the telescope and reducing the cost of all other components of the programme (excluding instrumentation) also required a reduction in the dimensions of the telescope.

The 42-metre E-ELT design was based on a three-mirror anastigmat used on-axis with two folding flat mirrors extracting the beam to a suitable Nasmyth focus (Spyromilio et al., 2008). This design was driven by the requirement for a Nasmyth focus, that the telescope be adaptive and the large diameter. These three basic requirements, combined with a number of engineering risks (e.g., the maximum size of the deformable mirror that was viable within cost and schedule constraints), confined the parameter space. Our competitors have chosen more classical designs: Ritchey-Chrétien (RC) in the case of the Thirty Metre Telescope (TMT) and Gregorian in the case of the Giant Magellan Telescope (GMT). We considered whether a smaller telescope would warrant completely new thinking in the optical design, but concluded that the incorporation of adaptive optics in the telescope is a prerequisite for the dimensions that we were considering. In addition to correcting the ground layer of atmospheric turbulence, the inclusion of an adaptive element in the telescope optical train allows us to manage the aberrations of the telescope under the disturbances of wind and gravity.

The design was therefore iterated around the existing solution. Reducing the volume of the telescope could be achieved by making the primary faster (lowering the *f*-ratio). However, consideration needed to be given to the difficulty of making the segments and the secondary mirror. After some investigation it was considered that making the telescope somewhat smaller and faster would provide us with cost savings in the dome, the main structure and the primary mirror, as well as reductions in manufacturing and performance risks.

Removing the two outer rings of the primary mirror segments results in a new telescope diameter of 38.54 metres for segments that are used fully and

39.1 metres if one includes the few segments that are illuminated for 80 % of their surface. The two rings accounted for approximately 200 segments from the original 984 installed in the telescope. The cost saving unfortunately is not a straight percentage of segment number as the facility costs (building the factory to produce the mirror segments and equipping it with the necessary polishing robots, etc) are relatively invariant at this scale of production. However, the risk of achieving the production goals and timescales are theoretically much reduced by the smaller number of segments.

Having lost three metres of diameter on the primary mirror of the telescope, we targeted cost savings in the other components that should be at least as dramatic. The dimensions of the dome were reduced further as we shrank the telescope Nasmyth platforms by five metres on each side, thereby reducing the dome diameter by more than 10 %.

In the redesign process, the project considered which risks could be further mitigated or reduced. The large secondary mirror (a convex 6-metre in the 42-metre case) posed a series of interesting manufacturing challenges and simultaneously posed a limitation in the performance of the telescope under heavy wind loading. Specifically, the secondary mirror deflections in the wind dominated the error budget for the 42-metre design and a feed-forward control scheme for the tip-tilt M5 mirror, based on accelerometer input from the secondary, might have been necessary to meet the performance goals in the most stringent of environmental conditions. However, given the need to reduce costs and risks, reducing the size of the secondary mirror, beyond what a simple scaling would imply, provided a useful focus for the re-baselining activities.

In manufacturing large optical elements there exists a natural break-point at diameters of around 4.2 metres that arises from a series of trade-offs that involve manufacturing facilities and dimensions of machines and processes. We therefore placed a 4.2-metre diameter constraint on the secondary mirror and evolved the optical design of the 39-metre E-ELT about that solution. We have maintained, to the maximum extent possible, the linear dimensions of the quaternary adaptive mirror. Effectively this provides a somewhat denser actuator spacing in comparison to the 42-metre design, as approximately the same number of actuators now cover a smaller primary mirror.

In order to maintain the field of view of the telescope with a smaller secondary, the telescope primary mirror is now faster at *f*/0.9. However the difficulty in polishing the segments of the primary mirror is comparable between the two designs.

The aspheric coefficients of the smaller secondary mirror are different but remain within the polishing regime considered for the 42-metre baseline 6-metre mirror. The polishing solution proposed by the ESO contractors for the convex 6-metre mirror employed transmission elements, known as matrices, for the metrology. The matrices are large optical elements that more or less match the radial curvature and local aspheric departure of the mirror and cover a fraction of the surface. The mirror is then rotated under the matrix while the cavity between the matrix and the polished mirror surface creates the interferometric cavity that is used to test the accuracy of the polished surface. For the 42-metre design with 6-metre secondary mirror, two matrix units would have been necessary. The new 4.2-metre mirror radius is within the reach of a single such matrix, thereby potentially greatly simplifying the polishing metrology and the risk of mismatched references.

Speeding up the focal ratio of the primary mirror and reducing the dimensions of the secondary, also reduced the length of the telescope, which reduced the overall weight and made it easier to achieve the required stiffness. The provision of the gravity-invariant focus under the Nasmyth platform had proved to be a design driver for the mechanical structure of the telescope, requiring significant amounts of steel reinforcement to provide the necessary stiffness for the instrumentation and the pre-focal station. Moreover, it complicated the support and load transfer to the azimuth tracks. By removing the gravity-invariant focus, speeding up the primary and reducing the dimensions of the Nasmyth platforms, the telescope main structure has lost a lot of weight (several hundreds of tonnes of steel) and engineering complexity.

Design activities

It has been challenging to evaluate these ideas and to bring the E-ELT project with this new concept to a comparable level of engineering as the phase B for the 42-metre design had achieved. In particular this re-baselining was to be performed within one calendar year and with limited resources. The Project Office placed a series of delta phase B contracts to update the previous design. A revision of the dome for the new parameters and a revision of the main structure were contracted to the firms that had developed the original concepts.

The new dome is simplified relative to the phase B concept in a number of critical areas. After an evaluation by the contractors and ESO of the erection sequence for the dome and the main structure, it became apparent that the large 30 × 17-metre loading door, foreseen to allow large telescope components to enter the dome without requiring the opening of the observing doors, was not necessary, and, furthermore, it added complexity in the concrete pier of the dome. It has been removed from the plans. The dome for the 42-metre telescope design had included a requirement for a lifting platform that allowed access to the Nasmyth platforms and also to the secondary mirror. The platform was required to lift 30 tonnes to 30 metres above the floor in order to support the exchange of the secondary mirror with its cell. While engineering solutions existed and the concept was elegant, alternate cheaper solutions based on cranes can be found to enable the necessary manipulations. Removing the platform has made it possible to configure the geometry of the telescope spider that supports the secondary mirror so that it better reflects the direction of the loads generated as the telescope is inclined.

In addition to the aforementioned changes to the Nasmyth platforms, the shorter telescope made it possible to

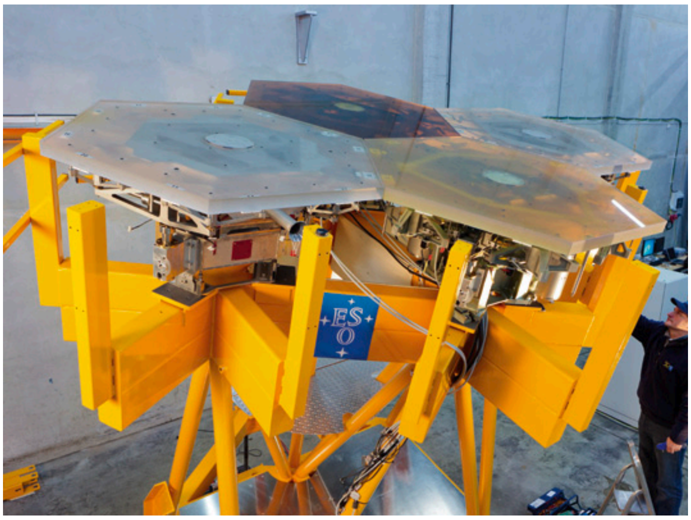


Figure 1. The segment test assembly in Garching. Four fully polished segments have been mounted on their supports. Edge sensors and actuators have been deployed on a number of the segments and control testing has started.

Figure 2. The seismic isolation test bed. Both the lateral and the vertical components of the earthquake acceleration are significantly diminished through this isolation device.

replace the carbon fibre in the spider with normal steel. This change removed one of the risks identified in the 42-metre design, and made it easier to balance the telescope.

In the area of opto-mechanics a number of activities continued throughout the delta phase B period. The secondary mirror unit contract, which was still running at the start of the delta phase B, was extended in time to cover the period of the new design. The prototyping of the polishing of the primary mirror segments is progressing on multiple fronts. One supplier has delivered to ESO segments that meet the specification for the most difficult to polish components of the primary mirror (see Figure 1). The technical feasibility of the primary mirror, we feel, is now without doubt. The project has continued to invest funds and manpower in following up different technologies for polishing with two additional suppliers: using, in one case, stress mirror techniques (as used for the Keck telescopes) and, in another case, a single, fully robotic, process. The stress mirror polishing has provided ESO with additional prototype segments and a strong interest from industrial partners to engage with the project.

Progress was also made in the area of actuators with further soft (low stiffness, high bandwidth) prototype units under construction. In the area of edge sensors the project has worked together with the suppliers to revise specifications and modify various requirements based on more detailed analysis of the results and the requirements.

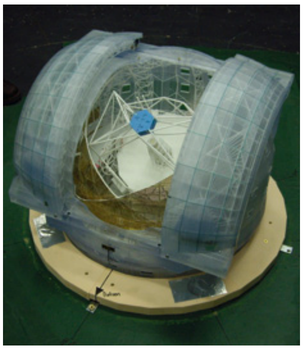
Prototype testing

During phase B and the delta phase B the project placed great emphasis on prototypes that demonstrated the practical feasibility of the designs and plans. The underlying principle was not only to test the design but also to familiarise ESO and our industrial partners with the difficulties and challenges ahead.

The E-ELT design employs seismic isolation systems to reduce the effects of ground accelerations on the dome and the main structure. Such systems are in common use in regions of high seismic risk but are usually made to isolate in the horizontal direction only. While for the dome this isolation would be sufficient, we have considered that for the telescope pier seismic isolation should include a vertical component. The challenge has been to provide the necessary isolation without reducing the stiffness of the telescope in normal operations. The necessary system was designed by the dome phase B design contractor in collaboration with providers of seismic isolation systems. During 2011 a scaled prototype system was built and tested on a large shake system (see Figure 2).

The wind tunnel testing of the dome and telescope main structure undertaken during the phase B were extended in the delta phase B to include the topography of the Cerro Armazones site. The wind tunnel results have been crucial in providing an alternate view to the computational fluid dynamics (CFD) analysis that is undertaken both in-house at ESO and by our contractors. Figure 3a shows the model used in the wind tunnel and Figure 3b a CFD simulation of the wind flow through the dome.

For the primary mirror, prototype systems have been delivered to ESO from two suppliers of primary mirror supports (including warping harnesses, extractors, packing and transporting systems, etc). Separate suppliers also delivered two sets of position actuators and a set of edge sensors. As mentioned above, a number of segments have also been manufactured. For the quaternary mirror, prototype systems have been manufactured for representative subassemblies of the mirrors, including polished deformable mirrors, electronics, actuators, etc. A complete electro-mechanical, scale one,



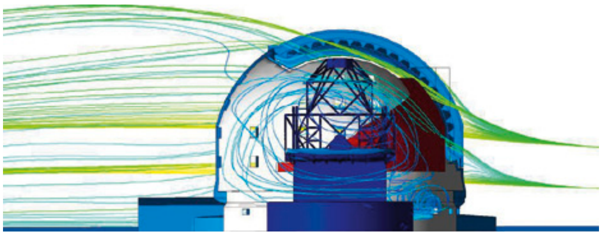


Figure 3. Figure 3a (left) shows a 1:200 scale model of the E-ELT in its dome used in the wind tunnel testing. Figure 3b (right) shows the modelled wind flow though the dome.

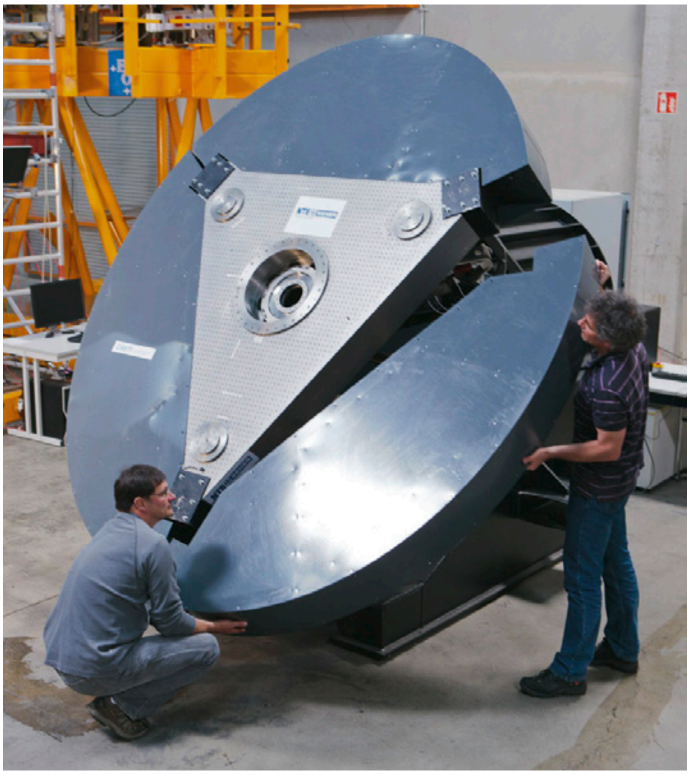


Figure 4. The electromechanical M5 prototype. In the centre is a dummy mirror that is moved in tip-tilt by three heavy-duty actuators mounted behind the system. The covers being installed by Pablo Barriga and Marin Dimmler give the full dimensions of the M5 mirror as it will be installed in the telescope.

unit has been manufactured for the tip-tilt M5 mirror (see Figure 4).

A scale one interlock system for the telescope and dome has been prototyped based on safety programmable logic circuits (PLCs). The timing system based on the IEEE 1588 standard has been demonstrated. This is a critical technology for the project as it avoids creating dedicated electronics and networks and can rely on commercial switches and networks, such as Ethernet, for the distribution of timing signals. Electronic prototype units have been constructed as demonstrators for the secondary mirror unit control and other units. During phase B industrial suppliers provided solutions for the telescope Real-Time Computer (RTC) needs. In particular a personal computer based RTC for adaptive optics was shown to be feasible and a scale one RTC for the telescope control is in construction.

The control concepts for the E-ELT move away from the monolithic integrated approach of the past, and rely on Component Off The Shelf (COTS) principles with which industry is familiar. This approach reduces the interface risk with industry. A number of these concepts have, or are being, proved in the field. In particular a prototype test of the E-ELT concepts was deployed at the Very Large Telescope (VLT) Unit Telescope 1 (UT1) dome at Paranal and is today used in operations by the observatory. The E-ELT technologies have been selected to prevent unmanageable obsolescence.

Almost all the hardware prototypes have been assembled in the E-ELT test facility located within the ESO warehouse facility in Garching Hochbrück. A stand that replicates the mirror cell structure has been built and four of the prototype segments have been mounted, complete with their support structures, actuators and edge sensors (Figure 1). The system has been tuned and the loop between the edge sensors and the actuators has been closed. The tests in Hochbrück include field tests of the control architecture and deployments of publish/subscribe components interfacing with COTS systems.

We continue to test phasing and control methodologies in technical time awarded at the 10.4-metre Gran Telescopio Canarias (GTC). This work has been extremely beneficial to our understanding of how segmented mirror telescopes are controlled and the co-operation between the GTC and the E-ELT project teams has been excellent.

New wavefront sensor detectors based on complementary metal-oxide semiconductor (CMOS) technology are under development for the E-ELT project. The prototype pixels were successful and we expect our first 600 by 600 pixel fast readout, low readout noise detector in the coming months.

The E-ELT project has contracted for the development of Vertical-External Cavity Surface-Emitting Lasers (VECSELs). These development contracts have resulted in prototype systems that are promising. In the context of the VLT Adaptive Optics Facility (AOF; see Arsenault et al., 2011), there is much ongoing work within ESO and contractors for lasers and laser launch telescopes. The E-ELT project is following this work closely as the requirements for the AOF and the E-ELT are very similar and the AOF fibre lasers form the baseline today for the telescope.

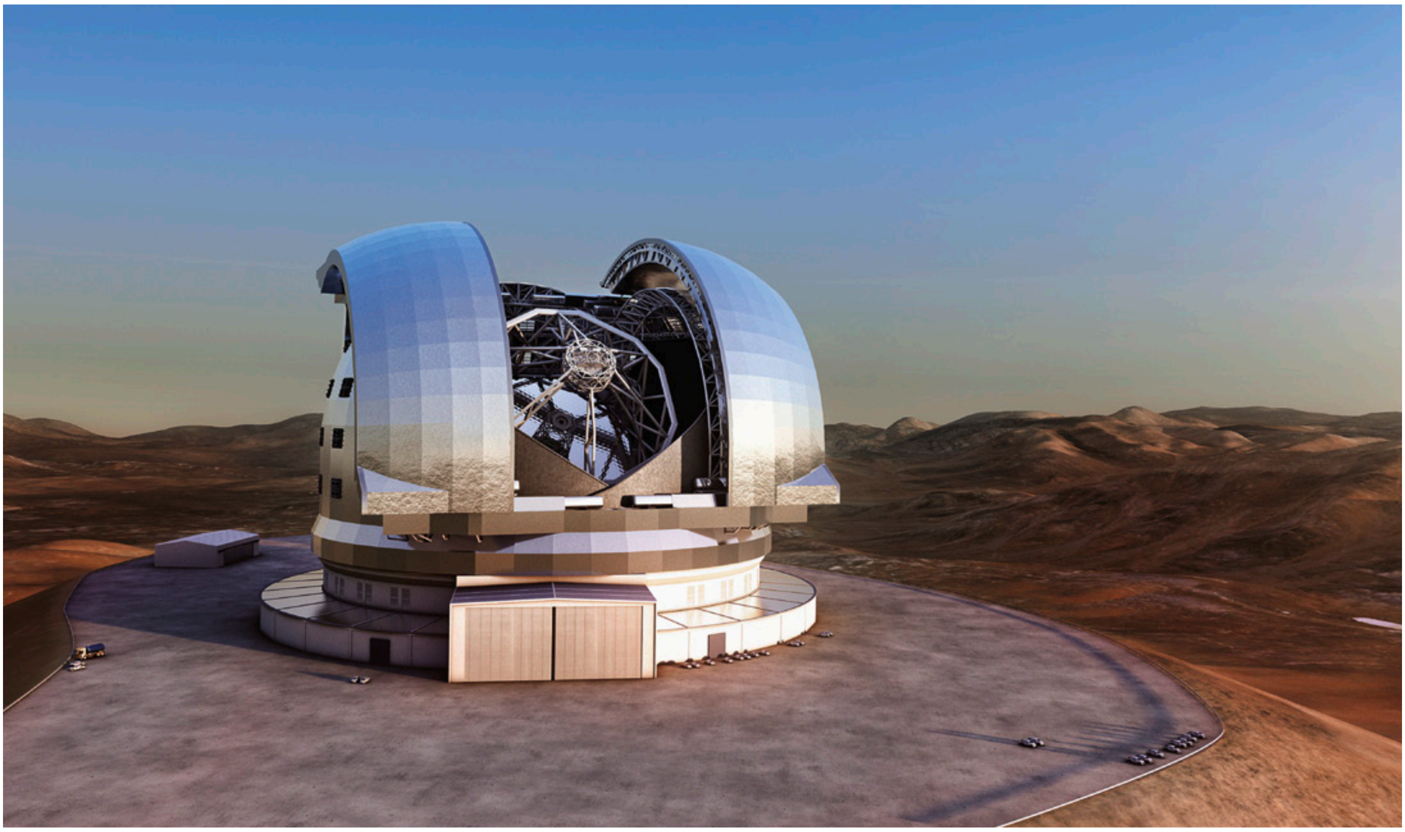


Figure 5. An impression of the E-ELT in its enclosure at Cerro Armazones.

Infrastructure

The Chilean government has agreed that ESO can incorporate the Cerro Armazones site in the Paranal Observatory[5]. This has been an important milestone for the E-ELT programme as the telescope is to be operated as an integral part of Paranal. The operational scenario presented in the construction proposal foresees that the day crew commutes from the Paranal base camp to Armazones thereby minimising the cost of additional facilities. A night crew will be resident on Cerro Armazones, but the control room is expected to be co-located with those of the UTs on Paranal.

To this purpose the design of the road linking the Armazones site with the Paranal road has had a high priority and is well underway. The more extended geotechnical survey of the Cerro Armazones peak revealed no surprises. Additional seismic testing is underway to characterise the amplification factor created by the focusing of seismic waves by the particular geometry of the peak.

Positive news is also available on the power generation front with activities undertaken by the ESO engineering directorate, the ESO representation in Chile and the Chilean authorities to support the connection of Paranal to the Chilean national grid.

Instrumentation

The instrumentation activities have resulted in conceptual designs for a number of instruments covering a broad range of capabilities (see D'Odorico & Ramsay, 2010). The instrumentation road map has been endorsed by the ESO Science and Technical Committee (STC) and presented as part of the construction proposal to the ESO Council.

The two first light instruments have been selected: a diffraction-limited imager operating in the near-infrared, fed by adaptive optics; an integral field spectrograph with a variety of plate scales ranging from the diffraction limit to seeing limited, fed by adaptive optics. The third instrument to be included in the construction project is a thermal infrared instrument. For this instrument, a technology demonstration of the detector is planned within the upgrade of the VISIR instrument at Paranal. Additional instruments are budgeted for and planned within the E-ELT programme and selections will be made in due time.

The interfaces to the observatory are under development within the ESO Instrumentation Division with support from the Directorate of Engineering.

Costing review and methodology

Analysis of costing methodologies in scientific projects, and in industry at large, showed that uncertainty in the design and lack of understanding of the risks increase the costs of projects between the cost-estimation phase and award of contract. With this in view, and with the aim of minimising this risk, the E-ELT has pioneered (at least in the field of astronomy) the concept of using competitive Front End Engineering Design (FEED) studies as the design vehicle before construction starts. These FEED contracts are awarded competitively, typically to more than one supplier, and provide not only a detailed design, but also a firm, fixed-priced offer for construction. Where feasible, the FEED contracts were combined with prototype construction at a limited scale.

By adopting this practice, the design process is not only competitive in the area of performance, but also in the area of cost. Moreover, the process provides detailed visibility of the structure and nature of the cost of design choices. It is certain that we have not retired cost risk from the project, but we consider that we better understand our cost risks. FEED offers underpin the construction proposal for the E-ELT.

Managerial

The project management structure has also evolved in preparation for construction. Council has appointed the project manager (Alistair McPherson; see profile on p. 53) to lead the construction effort and the post of project engineer has been advertised; by the time this article is in print it is expected to have been filled.

The work breakdown structure and product trees have been updated and synchronised with the budget for the construction. Technical reviews of the work undertaken by our contractors have taken place during the design process. The E-ELT has contracted expert external firms to assist the reviews of very large subsystems (e.g., the dome and main structure). Additionally the E-ELT has used external companies to verify and critique the requirements of the project, with a view to manufacturability and cost, as well as performance. As often as possible, the contracted work has been awarded to more than one supplier, providing not only a competition in cost and design, but also two independent assessments of the ESO requirements.

Three formal reviews of the project were undertaken. The first technical and managerial review of the complete phase B package took place in late 2010. A cost review took place in late 2011. Both review boards were comprised of experts drawn from the construction and management of large scientific infrastructures. A further cost, risk and management review was undertaken in late 2011 by an industrial firm specialising in such matters. All reviews gave the E-ELT project very good reports and useful feedback.

Prospects

The E-ELT project has matured from the end of phase B in 2010 and is prepared for a start of construction as soon as the ESO Council gives the go-ahead.

Acknowledgements

The authors thank all the participants and participating institutes in the instrumentation studies (see articles in *The Messenger*, 140, p. 17–39) and the advisory bodies and review committees that have guided the project so far. While the credit belongs to the many contributors to this work, the authors take responsibility for all errors.

Much of the work described was undertaken under contract from ESO by industrial firms, amongst whom were: Active Space (Portugal); ADS (Italy); AMOS (Belgium); ARUP (UK); ASDEA (Italy); BCD (Italy); Boostec (France); Bronto Skylift (Finland); CESA (Spain); CILAS (France); CIRA (Italy); Corning (USA); Critical Software (Portugal); CSEM (Switzerland); Demont (Italy); DSL (Canada); e2v (UK); EAI (Spain); EIE (Italy); Fogale (France); Franklin & Andrews (UK); IDOM (Spain); INES (Switzerland); ISQ (Portugal); ITT (USA); Kirkholm (Denmark); KN Systemes (France); L3Com Brashear (USA); L3Com Tinsley (USA); Laboratoire D'Astrophysique Marseille (France); MicroEpsilon (Germany); Microgate (Italy); Micromega Dynamics (Belgium); MTMechatronics (Germany); National Instruments (USA); NTE/SENER (Spain); Observatory Sciences Ltd (UK); Optic Glyndwr (UK); ORC (Finland); Physik Instrumente (Germany); Rovsing (Denmark); Sagem (France); Sarnoff (USA); Schott (Germany); SciSys (UK); SESO (France); Siemens (Germany); SIRVE (Chile); Solving (Finland); Space Systems Finland (Finland); Threon (Germany); TNO (the Netherlands); UKATC (UK); University of Liege (Belgium); USB (Germany); Weatherpark (Austria).

References

Arsenault, R. et al. 2011, The Messenger, 142, 12
D'Odorico, S. et al. 2010, The Messenger, 140, 17
Gilmozzi, R. & Kissler-Patig, M. 2010, The Messenger, 143, 25
Spyromilio, J. et al. 2008, The Messenger, 133, 2

Links

[1] E-ELT Construction Proposal: http://www.eso.org/public.archives/books/pdf/e-elt_constrproposal.pdf
[2] E-ELT Board report: http://www.eso.org/sci/facilities/eelt/docs/E-ELT-PhaseB-BoardReport_Exec-Summary.pdf
[3] E-ELT Design Reference Mission: http://www.eso.org/sci/facilities/eelt/science/doc/drm_report.pdf
[4] E-ELT Design Reference Science Cases: http://www.eso.org/sci/facilities/eelt/science/eelt/drm/cases.html
[5] Agreement signed between Chilean government and ESO for Cerro Armazones site: http://www.eso.org/public/news/eso1139/