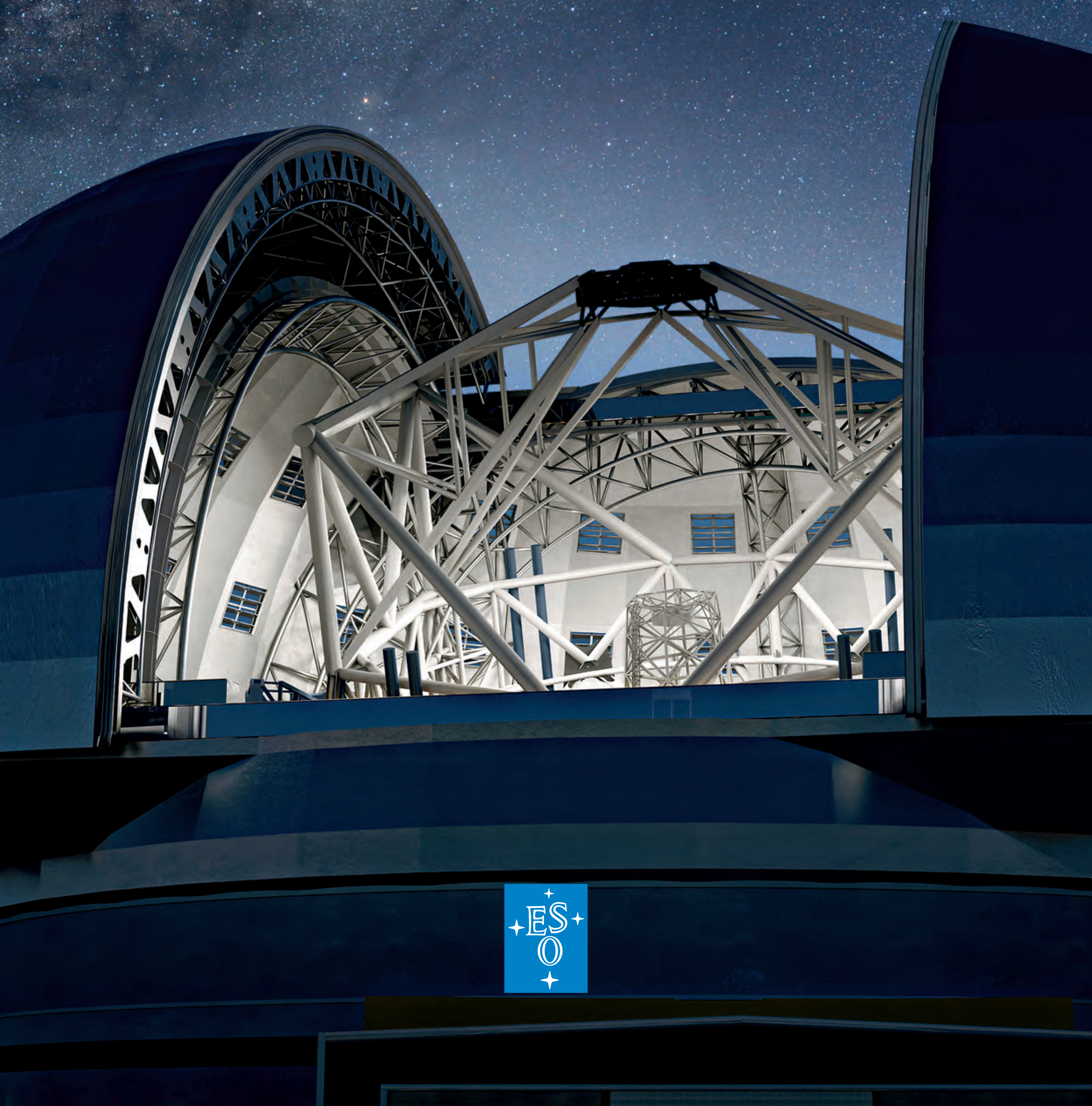
THE E-ELT CONSTRUCTION PROPOSAL

Executive Summary & Proposal Digest



Executive Summary

This document presents a 1083 million euro (M€), 11-year programme for the construction of the European Extremely Large Telescope (E-ELT), the facility that will maintain the European Southern Observatory (ESO) in its leading position providing research capabilities to the European astronomical community for the coming decades. Specifically, it is proposed to construct a 39.3-metre segmented optical telescope on Cerro Armazones as part of the La Silla Paranal Observatory, proven to be one of the world's best astronomical sites. The telescope will be operated from, and as part of, the existing Paranal site. This will create an outstanding facility in Chile for ESO Member States and will ensure that the maximum advantage can be taken of developments within astronomy and engineering.

This construction proposal includes not only the telescope structure and enclosure, but also all of the optics and instrumentation required to establish this unique scientific facility. Although it will be built as part of the existing infrastructure, extensions to roads, power supplies and services will be required to maintain and operate the facility. In addition, such a powerful telescope requires an array of instruments to achieve its ambitious science goals. This construction proposal includes a plan that will deliver several instruments to the telescope and it provides the roadmap and technology development to enable further instrumentation for the future exploitation of the facility. This plan ensures that the telescope will operate with two instruments when it enters service, with one further instrument being delivered every two years thereafter.

Figure 1. Sunset from Armazones (as it will be seen at first light of the E-ELT).

The telescope has a mirror 39.3 metres in diameter, viewing an area on the sky about one ninth the size of the full Moon. The optical design itself is based on a novel five-mirror scheme that delivers exceptional image quality. The primary mirror consists of 798 segments, each being 1.45 metres wide but only 50 millimetres thick.

To take the maximum advantage of the site, the available technology and developments in instrumentation, the telescope will be adaptive, automatically correcting the disturbances introduced by the Earth's atmosphere before the light enters the instruments. This follows the development of the adaptive optics deployed on Very Large Telescope (VLT) instrumentation and is an evolution of the Adaptive Optics Facility being developed for the VLT. The telescope will be delivered with an adaptive 2.4-metre mirror and will utilise six sodium laser guide stars.

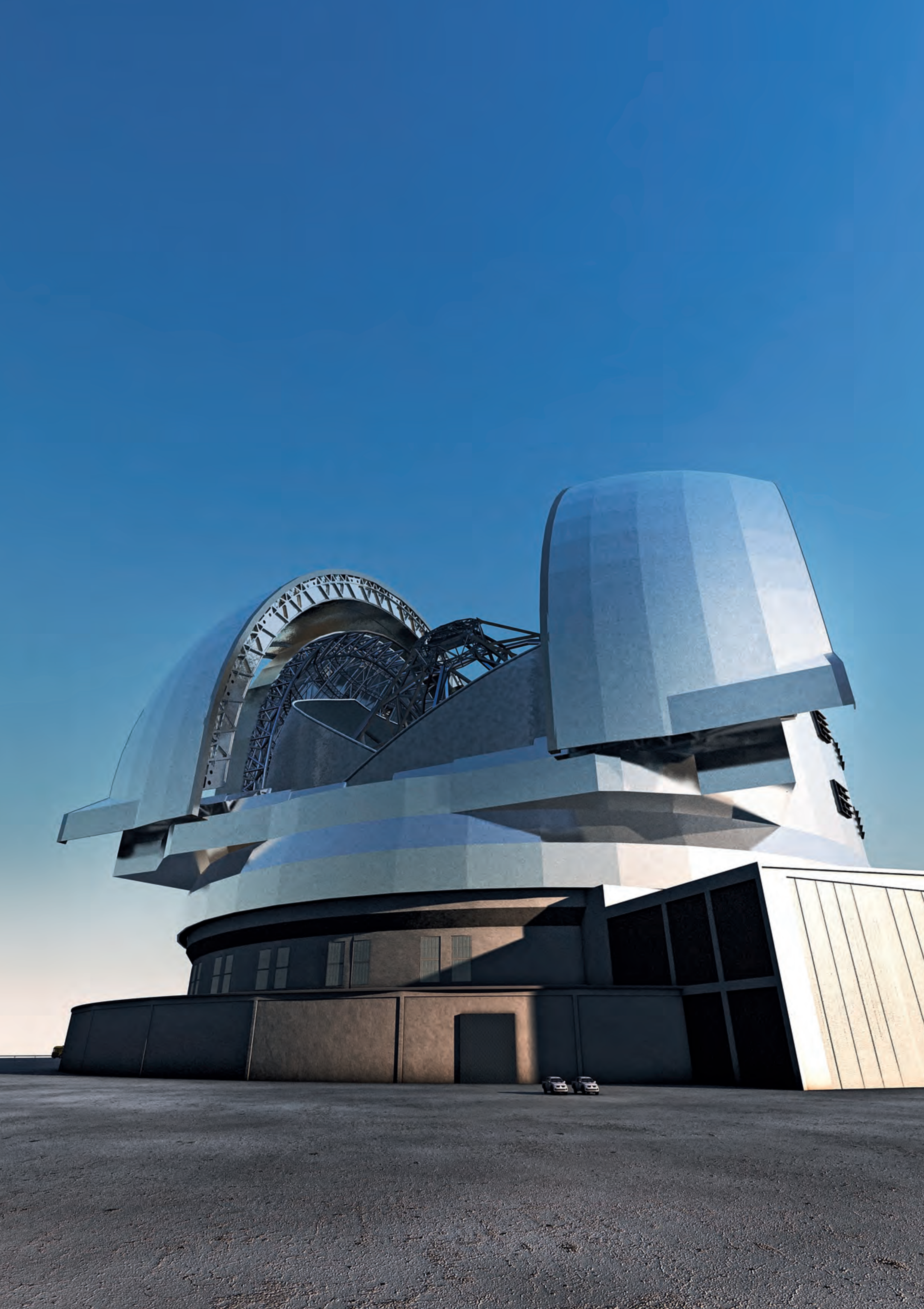
Developing the E-ELT is a major endeavour in science, technology and engineering. Partnerships between institutes, universities and industry are already forming to build and exploit the telescope, its systems and instruments. In addition, the technologies and innovations being developed to deliver the E-ELT have already found, and will continue to find, wider applications within industry. Adaptive optics and lasers are two such areas already being spun out.

It is clear that a project of the size and technological challenge of the E-ELT will have a significant economic, cultural and scientific impact with a good chance of direct applications in areas such as medicine. The development of the E-ELT will generate knowledge, provide inspiration, increase our skills base and develop industrial capacity.

The E-ELT will be the first extremely large telescope on Earth and will take full advantage of the discoveries made by the James Webb Space Telescope (JWST).

The work carried out to date, primarily with industry, has reduced the risk for both the technical demands and the management of the programme. Following successful technical and financial reviews, the programme is in an excellent position to move into construction, and the timing would ensure that Europe maintains its world lead in large astronomical facilities and the resulting research and discovery benefits.

This proposal is concerned mainly with the technological challenges of building the E-ELT, but its main aim is to provide a facility that will allow the community to tackle the exciting scientific questions addressed by the E-ELT science case. Should the governments of the ESO Member States come to a rapid decision about authorising the programme, the involvement and leadership of Europe in these discoveries will be assured.



Proposal Digest

Introduction

The following text comprises Chapter 1 of the full E-ELT Construction Proposal and is intended to provide the reader with an overview of the essential elements of the full E-ELT proposal.

Science with the E-ELT

The next step in four hundred years of discoveries

The European Extremely Large Telescope is the next giant step in four centuries of astrophysical research using telescopes. The year 2009 marked the passing of 400 years since Galileo Galilei first used a telescope for astronomical research, making the ground-breaking observations that would finally refute the geocentric Ptolemaic worldview and establish the heliocentric Copernican one. Since then, astronomical observations with telescopes have increasingly become the norm, until today, when observatories around the world host giant telescopes that work every available second to collect immense quantities of data. Each technological advance has brought new, and often totally unexpected, discoveries about our Universe, enriching our cultural heritage.

Over the last sixty years, astronomers have developed telescopes that are able to observe right across the electromagnetic spectrum. Antennas for long wavelength observations — radio, millimetre and submillimetre — were constructed, allowing many scientific breakthroughs, such as the discoveries of quasars, pulsars, the cosmic microwave background, and much more. Further, space observatories allowed observations to be pushed to shorter wavelengths, into the ultraviolet, X-ray and gamma-ray regimes. This opening up of the high energy frontier generated a further flood of discoveries such as X-ray stars, gamma-ray bursts, black hole accretion discs, and other exotic phenomena. Previously unknown physical processes were taking place in the Universe around us. These astrophysical discoveries led to a number of Nobel Prizes in Physics (in 1974, 1978, 1993, 2002, 2006 and 2011) and to giant leaps in our understanding of the cosmos.

While astronomy has expanded to encompass these new wavelength bands, most discoveries are still made in the visible and near-infrared regimes, where stars predominantly emit their light. Technological advances in the 1980s and 1990s allowed scientists to build ever larger telescopes and ever more sensitive cameras. These instruments have opened up whole new areas of study. For example, the first exoplanets (planets orbiting other stars) were detected, and the current generation of 8–10-metre-class telescopes has even allowed us to take the first pictures of a few of these objects. Another example is the indirect detection of dark energy, previously completely unsuspected, but believed today to dominate and drive the expansion of the Universe. Our knowledge in astronomy continues to progress at an incredible pace, answering many questions, but also raising exciting new ones.

The European Extremely Large Telescope will be key in addressing these new questions and, in the sections that comprise Chapter 1 of the full E-ELT Construction Proposal, we seek to give a flavour of the kind of fundamental questions that it will finally answer. However, just as Galileo was astounded to find mountains on the Moon and moons orbiting Jupiter, the most exciting discoveries are probably those that we have not yet even imagined.

Open questions for the E-ELT

A revolutionary telescope such as the European Extremely Large Telescope is designed to answer some of the most prominent open questions in astrophysics.

Exoplanets: Are we alone?

For over a decade, we have known that exoplanets exist, but we have not yet been able to detect the faint signatures of Earth-like planets directly. The E-ELT will have the resolution to obtain the first direct images of such objects, and even analyse their atmospheres for the biomarker molecules that might indicate the presence of life.

Are planetary systems like the Solar System common? How frequently do rocky planets settle in "habitable zones", where water is liquid on the surface? Do the atmospheres of exoplanets resemble those of the planets in the Solar System? How is pre-biotic material distributed in protoplanetary discs? Are there signs of life on any exoplanets?

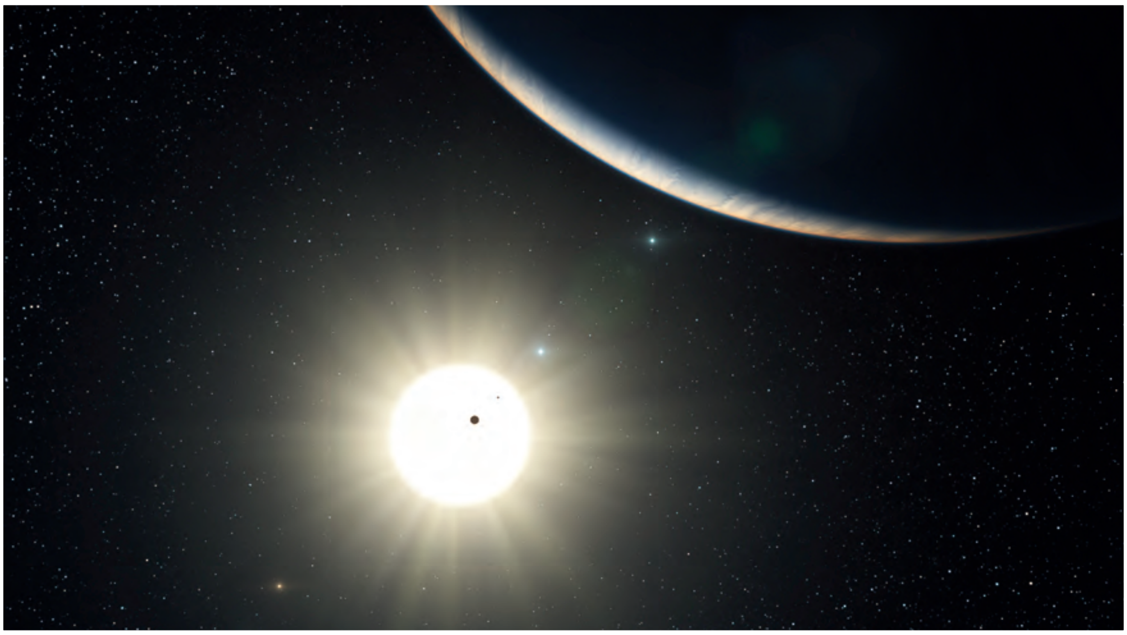


Figure 2. An artist's conception of a multi-planet system as they are commonly found now around nearby stars.

Fundamental Physics: Are the laws of nature universal?

As far back in time and as far out in distance as we can observe, all phenomena that have yet been investigated seem to indicate that the laws of physics are universal and unchanging. Yet, uncomfortable gaps exist in our understanding: gravity and general relativity remain to be tested under extreme conditions, the amazingly rapid expansion (inflation) of the Universe after the Big Bang is not understood, dark matter seems to dominate the formation of the large-scale structure, but its nature remains unknown, and the recently discovered acceleration of the expansion of the Universe requires a mysterious dark energy that is even less comprehensible.

Were the physical constants indeed constant over the history of the Universe? How did the expansion history of the Universe really proceed? Can we infer the nature of dark energy?

Black Holes: What was their role in shaping the Universe?

Black holes have puzzled physicists and astronomers since they were first postulated in relativistic form a century ago by Karl Schwarzschild. Observations have demonstrated that these bizarre objects really do exist. And on a grand scale, too: not only have we found black holes with masses comparable to stars, but supermassive black holes, a million or even a billion times more massive than the Sun, have also been found at the centres of many galaxies. These black holes also seem

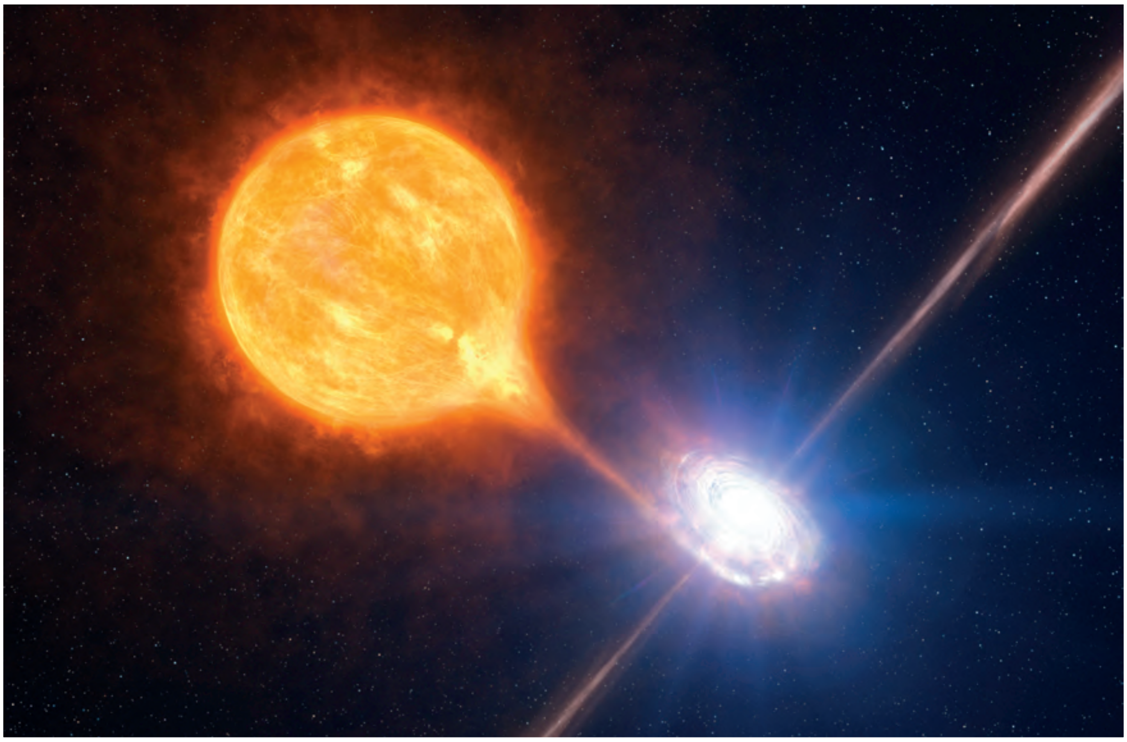


Figure 3.
An artist's conception of a neutron star, collapsed to a black hole, accreting and ejecting material from its red giant companion.

to “know” about the galaxies they live in, as their properties are closely correlated with those of the surrounding galaxy, with more massive black holes being found in more massive galaxies.

Will studies of the supermassive black hole at the centre of the Milky Way reveal the nature of these objects? Do theories of gravitation and general relativity as we know them hold near a black hole’s horizon? How do supermassive black holes grow? And what is their role in the formation of galaxies?

Stars: Don’t we know all there is to know?

Stars are the nuclear furnaces of the Universe in which chemical elements, including the building blocks of life, are synthesised and recycled: without stars there would be no life. Accordingly, stellar astrophysics has long been a core activity for astronomers. But much remains to be understood. With higher angular resolution and greater sensitivity astronomers will be able to observe the faintest, least massive stars, allowing us to close the current huge gap in our knowledge concerning star and planet formation.

Nucleocosmochronometry — the carbon-dating method as applied to stars — will become possible for stars right across the Milky Way, allowing us to study galactic prehistory by dating the very first stars. And some of the brightest stellar phenomena, including the violent deaths of stars in supernovae and gamma-ray bursts, will be traced out to very large distances, offering a direct map of the star formation history throughout the Universe.

What are the details of star formation, and how does this process connect with the formation of planets? When did the first stars form? What triggers the most energetic events that we know of in the Universe, the deaths of stars in gamma-ray bursts?

Galaxies: How do “island universes” form?

The term “island universes” was introduced in 1755 by Immanuel Kant and used at the beginning of the 20th century to define spiral nebulae as independent galaxies outside the Milky Way. Trying to understand galaxy formation and evolution has become one of the most active fields of astronomical research over the last few decades, as large telescopes have reached out beyond the Milky Way. Yet, even nearby giant galaxies have remained diffuse nebulae that cannot be resolved into individual stars. The unique angular resolution of the E-ELT will revolutionise this field by allowing us to observe individual stars in galaxies out to distances of tens of millions of light-years. Even at greater distances, we will be able to make the kind of observations of the structure of galaxies and the motions of their constituent stars that previously have only been possible in the nearby Universe: by taking advantage of the finite speed of light, we can peer back in time to see how and when galaxies were assembled.

What kinds of stars are galaxies made of? How many generations of stars do galaxies host and when did they form? What is the star formation history of the Universe? When and how did galaxies as we see them today form? How did galaxies evolve through time?

Figure 4. Centaurus A, 11 million light-years from the Milky Way, is our nearest giant galaxy collision.

The Dark Ages: Can we observe the earliest epoch of the Universe?

For the first 400 000 years after the Big Bang, the Universe was so dense and hot that light and matter were closely coupled. Once the Universe had expanded and cooled sufficiently, electrons and protons could recombine to form the simplest element, neutral hydrogen, and photons could decouple from matter: the Universe became transparent. Only then could the first stars form and start to become organised into larger structures. The E-ELT will allow scientists to look all the way back to these earliest times — prior to the formation of the first stars and hence dubbed the Dark Ages — to see how this first phase of astrophysical evolution began.

What was the nature of the first stars? When did the first galaxies assemble and what were their properties? When did galaxies assemble into larger-scale structures, shaping the distribution of matter as we see it today?

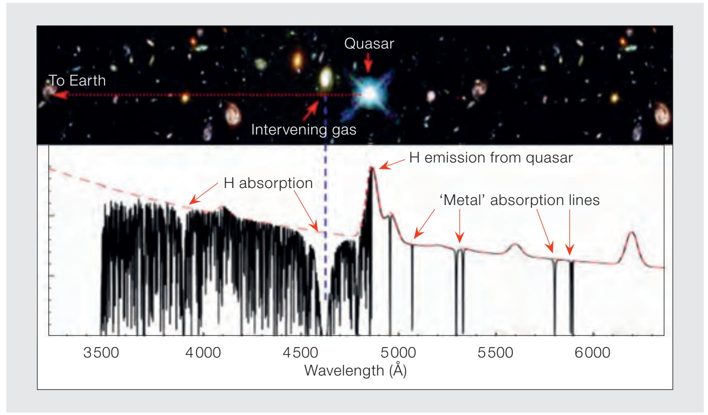


Figure 5.
The light of distant quasars is absorbed by a variety of components of the Universe on its way to Earth.

These illustrations merely hint at the science that the E-ELT will carry out, but they give a flavour of the range of problems that it will enable us to tackle, from the origins of the laws of physics to the prevalence of life in the Universe. It will allow scientists to address some of the most fundamental current questions, as well as opening up whole new frontiers of human understanding.

The astrophysical landscape beyond 2020

The E-ELT is built to address a very broad astrophysical landscape. Predicting what this will look like between 2020 and 2030 can only be incompletely drafted now. However, planned (i.e., not yet existing) facilities always have some degree of uncertainty attached to them and the exact progress in the relevant scientific fields will also depend on the success of upcoming facilities. The following summary focuses on the facilities and missions that bear most closely on the E-ELT science case.

In 2020, ESO will have operated the VLT for more than two decades. A large fraction of the breakthrough science within the capabilities of the 8–10-metre-class telescopes will have been achieved and consolidation work will dominate. Among the second generation of ESO VLT instruments, MUSE (the wide-field Integral-Field Unit [IFU] optical spectrograph), KMOS (the near-infrared, deployable IFU spectrograph), SPHERE (the planet imager), ESPRESSO (the ultra-stable, high-resolution spectrograph) and potentially one other instrument will have been in use for several years. The La Silla Observatory is likely to be operated at low cost and only for specific large programmes (e.g., similar to the HARPS survey). The survey telescopes, the VLT Survey Telescope (VST) and the 4.1-metre Visible and Infrared Survey Telescope for Astronomy (VISTA), will have finished their first set of large surveys delivering follow-up targets, many too faint for the VLT.

Perhaps more importantly, the submillimetre array ALMA will have been collecting data in full science mode for several years and will have pushed back the frontiers in many scientific areas, predominantly in studies of the high-redshift Universe and star and planet formation.

On the ground, no breakthrough facilities beyond the existing 8–10-metre-class telescopes and potentially a few additional, smaller survey telescopes will be operating, but several game-changing facilities are expected to emerge on the same timescale as the E-ELT: the Large Synoptic Survey Telescope (LSST), as well as the 24-metre Giant Magellan Telescope (GMT) and the 30-metre Thirty Meter Telescope (TMT) optical–near-infrared telescopes. The latter two represent some competition to, as well as complementing, the E-ELT and are discussed further in the full Construction Proposal. The Square Kilometre Array (SKA) is expected to appear in the decade following the E-ELT and to mainly build on breakthroughs in cosmology.

In space, the JWST might be operating within its five-year minimum lifetime and about to enter its anticipated five-year extension. A dedicated workshop highlighted the strong synergy expected between the JWST and the E-ELT. Current missions such as the Hubble Space Telescope (HST), Spitzer, Herschel, Planck, Kepler will have ended, others might still be flying, but reaching the ends of their lifetimes: Chandra, XMM-Newton, etc. A few new missions such as BepiColombo and Gaia on the European side will be operating; new ones (such as EUCLID, PLATO and LISA) are likely to be launched in the decade following the E-ELT's first light.

Close to the E-ELT science case, many research areas are expected to have progressed significantly by 2020. Thanks to radial velocity surveys (e.g., HARPS, ESPRESSO), but also dedicated imaging surveys (e.g., MEarth, HAT-Net, etc) and missions such as CoRoT, Kepler and Gaia, the catalogue of exoplanets is likely to have become very extensive. While the discovery of super-Earths in habitable zones is not excluded, it will remain the exception. Neptune- to Jupiter-mass planets will be known in great numbers enabling progress in planet formation theory. Direct imaging of giant planets distant from their parent stars will be nearly routine. Several stellar atmospheres of (mostly transiting) Neptune- to Jupiter-like planets will have been coarsely studied. The emphasis in exoplanet research will less likely be the discovery, but rather the characterisation, of exoplanets, with the notable exception of Earth-like planets in habitable zones: to be discovered.

In the domain of star formation, ALMA and JWST following from Spitzer, SOFIA and Herschel will be making enormous progress. Yet, the picture will remain incomplete as the inner few astronomical units of protoplanetary discs — including the habitable zone and inner rim of the protostellar disc — will await the insights to be generated by the E-ELT's high spatial resolution.

The study of galaxy formation and evolution is the declared strength of the JWST. The JWST will enable the study of mass assembly and chemical evolution of high-redshift galaxies by observing their stars and ionised gas. ALMA will complement these studies by observing the cold gas in these galaxies. Yet again, both facilities will have outstanding sensitivity but lower spatial and spectral resolution, which are the strengths of the E-ELT. While a census, and general picture, of the formation of the highest redshift galaxies is to be expected, a detailed understanding of these objects, anticipated to be of small size, will await the E-ELT.

Planned surveys aiming at the better understanding of dark energy will have started (e.g., DES, HETDEX, BigBOSS, EUCLID, WFIRST), complementing the anticipated results of the Planck mission, which is following on from the WMAP mission. The nature of any discovery in this domain is speculative. Ultimately, the direct measurement of the cosmic expansion, only possible with the E-ELT, will allow a fundamentally new approach to measuring the effect of dark energy.

Finally, a number of current and forthcoming space missions will explore our Solar System. The E-ELT promises to be a valuable contributor to understanding the formation of our Solar System, and thus of exoplanets.

Towards the E-ELT Concept

The E-ELT programme follows on from the early work by ESO on extremely large telescopes (with a diameter of 100 metres) undertaken in the late 1990s and early this millennium. This work culminated in a design review in November 2005 with concrete recommendations for future work. A period of intense community consultation took place in the first half of 2006 with five working groups, comprising a mixture of ESO and community experts, that established a starting point for a new baseline design for the telescope based on five reports: on science, site, telescope, instrumentation and adaptive optics.

Initially a 42-metre diameter anastigmatic telescope, incorporating rapidly deformable mirrors in the optical train and providing gravity-invariant foci for instrumentation, was selected as the starting point for the E-ELT. In the second half of 2006, a project office was established and, by the end of the year, the baseline reference documentation was submitted to the ESO Council as a proposal to move to a detailed design phase. The ancillary information governing this phase B included a management plan, a cost-estimating plan, a resource plan and a schedule. Subsequently this was replaced by the new baseline for a 39-metre diameter telescope with considerably reduced risk and cost.

Costing Philosophy

From the outset ESO strived to establish the technical and managerial feasibility of the project based on technologically demonstrated industrial input. During the design phase, described in the Design Process section below, the project has followed a consistent philosophy:

- ESO should develop the system-level requirements from the top-level science requirements;
- The design, including the cost and schedule for each subsystem, should be done in competition by industry and reviewed by independent industrial teams;
- The risk associated with high-risk items should be mitigated wherever possible by prototyping, done predominantly in competition by industry.

This has been implemented by using a technique known as Front End Engineering Design (FEED). Multiple competitive FEED studies have been carried out by European industry and reviewed by both the E-ELT project team and separate engineering consultants. All FEED contracts provide as their output, not only the detailed design and all the necessary documentation to put that design out to tender, but also binding cost and schedule estimates backed by firm fixed price offers to construct. As such the FEED offers are only one (ESO) signature away from being fully implemented contracts. They contain profit and the vendor's margin in order to complete the work for a firm fixed price, to an agreed schedule and with penalty clauses for late delivery. The final contracts will of course be the result of a new round of competitive procurement across the Member States of ESO. However this approach results in a well-qualified design with a very robust cost and schedule estimate. Of course, since these are real contract offers, they must be interpreted as such when assessing the cost and schedule risk of the project.

In parallel with the industrial studies that form the basis for the telescope design, ESO has engaged the astronomical community in the Member States for the development of an instrumentation package that matches the telescope and delivers on the science drivers for the project. Consortia of external institutes, based on initial guidelines from ESO, carried out the instrumentation studies. Eleven different concepts were considered, with over 40 institutes participating in the work. All design concepts were formally submitted by the end of 2010 and subsequently reviewed. Detailed manpower, schedule and cost estimates have been established at the phase A level.

Oversight and guidance to the project have been provided through a variety of committees drawn from the astronomical community at large. The Science Working Group (SWG) worked directly with the project scientist to develop design reference cases and to provide feedback on the capabilities of the telescope and instrumentation as these evolved during the design phase. The Site Selection Advisory Committee (SSAC) received input from the project and advised the Director General. The ELT Science & Engineering (ESE) subcommittee of the ESO Scientific and Technical Committee (STC), with membership overlap with the SSAC and the SWG, followed all aspects of the project and advised the STC and, in turn, the Director General and Council. Finally, the ELT Standing Review Committee (ESRC) reviewed high-level strategic and managerial aspects of the project and provided direct input to Council. Regular updates of the project progress were made to the ESO Finance Committee (FC).

External industrial consultancy was sought by the project for reviews of design and schedule/cost for major subsystems. Astronomers and engineers from ESO and external institutes reviewed the instrumentation reports. The SWG, ESE and STC were involved in this process at all times.

The Cost of the E-ELT

The cost to construct and commission the E-ELT is 1083 M€[1] including contingency, ESO staff costs and instrumentation.

The budget for the telescope (including the dome, optics, main structure all site civil works, ESO staff costs etc., but without contingency and instrumentation) is 883 M€. Of this 473 M€ (53%) is in firm fixed-price FEED offers.

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[1] ESO's budget is indexed every year to compensate for inflation; therefore all costs in this document are in 2012 euros.

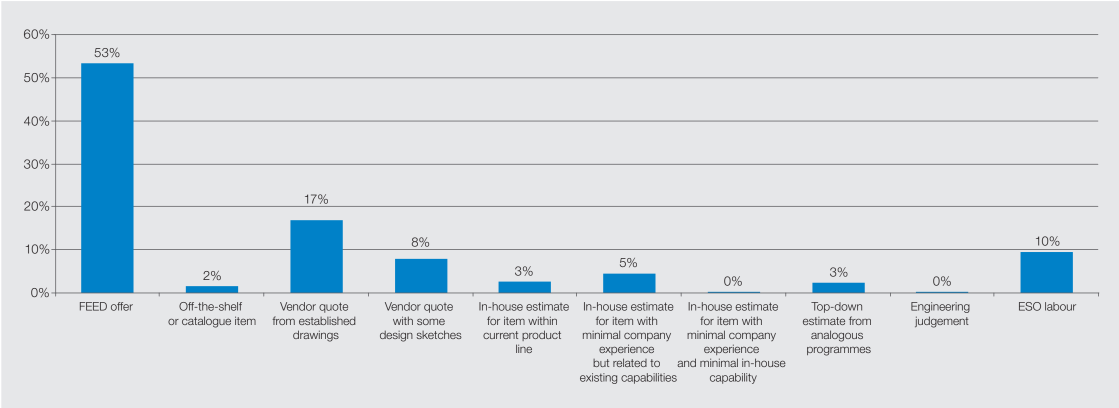

Figure 6. The distribution of the basis of the estimate of the costs of the E-ELT excluding instrumentation and contingency. 53% is in firm fixed price FEED offers.

The Schedule of the E-ELT

Assuming a January 2012 start, the E-ELT programme will take approximately 11 years to execute. Key major milestones are:

- Dome acceptance — March 2017;
- Main structure acceptance — March 2020;
- Technical first light — December 2021;
- Instrument 1 and 2 first light — June 2022;
- Start of observatory operations — October 2022.

Contingency

Telescope

The E-ELT budget carries a formal 100 M€ allocation of contingency to cover the risk of building everything except the instrumentation. This budget has been checked in two different ways:

- By comparing with the cost to complete and the FEED offers;
- Bottom-up, by looking at the uncertainty of each element of the Work Breakdown Structure (WBS).

Contingency compared to the cost to complete and FEED offers

Because the FEED offers are firm fixed-price contract offers, it is informative to calculate the uncommitted budget if all the FEEDs were to be executed. In this case 473 M€ of the project would immediately be under contract and the 100 M€ of contingency would be 24% of the uncommitted cost to completion. In reality the FEEDs will be competed for again, but the cross-check on the contingency level is reassuring.

Contingency by looking at the uncertainty of each element of the WBS

For the FEEDs, contingency is needed to cover the cost of change orders throughout the life of the contract. This is conservatively estimated to be 5%, although ESO's experience of change orders on large contracts is considerably better than this. The contingency required to cover the uncertainties in the remaining 47% of the budget is of course higher and has been estimated using the standard methodology used for ALMA (which is based on the method used in the US Department of Energy and by the National Science Foundation [NSF] for large projects). Using this approach, the total bottom-up contingency requirement is 86 M€, which again compares favourably with the 100 M€ available.

Instrumentation

The situation with the instrumentation is very simple. The instrumentation WBS has a ring-fenced budget of 100 M€. This is the construction component of what will be an ongoing instrumentation line of approximately 9 M€ per year. Based on the current cost estimates, the 100 M€ is sufficient to fund the first four instruments, ESO's management of the instrumentation programme and to carry out enabling technology Research and Development (R&D). However, if the cost of the instruments varies as the designs mature (they are only at phase A, which is beyond conceptual design, but not yet at preliminary design level), then the *scope* of what can be delivered within the 100 M€ will be adjusted. The balance of the instrumentation roadmap will be executed from the continuing instrumentation line which starts to ramp up in 2019.

The Construction Review and the Delta Phase B

A technical review in the second half of 2010 found the 42-metre concept to be technically sound and the cost estimates reliable. Concern was expressed regarding the ambitious schedule for such a complex telescope and the recommendation made that the ESO management be prepared for a two–three year extension of the eight-year schedule.

Following phase B, the project has undertaken a series of risk mitigation and cost reduction activities. The project and the technical review concurred that the most challenging areas of the project were the timely completion of the primary mirror segments, the manufacturing of the secondary unit and dealing with the high sensitivity of the telescope to wind loading.

A modified design was adopted by the project in 2010 establishing a 39-metre alternate which has become the baseline design. The resulting telescope is smaller, but also easier to build, faster to erect and more manageable in every aspect. The changes made to the design have been subjected to external industrial review. Without going into the detail that is presented in the full Construction Proposal it is important in this introduction to establish why the smaller E-ELT is a substantially better telescope, other than its manifest increased likelihood of being built, if scientifically somewhat less capable, than the 42-metre version.

The 39-metre telescope has a smaller and faster primary mirror. The reduction in the total number of segments is of order 20%. The fractional cost reduction is smaller than the reduction in telescope size as the non-recurring expenditures account for almost 50% of the total cost of the primary. However, the reduction in schedule risk is significant. The faster and smaller primary mirror allows the design to be optimised for a secondary mirror below 4.2 metres. This critical change permits a realistic diversity of supply in the procurement of the secondary unit. Moreover, the polishing of the convex mirror would only require a single matrix, thereby reducing the complexity and schedule of procuring the test setup. The mechanical safety of the unit under earthquake loading would also be easier to achieve. The other units of the telescope largely scale with the diameter and become proportionally easier to construct. A large benefit of the redesign is the reduction of telescope length and width, thereby reducing the dome volume and the exposure of the telescope to wind disturbances.

The Cost Review

The cost of the E-ELT, including the contingency and the construction schedule, was subjected to an in-depth external review in September 2011. The Cost Review Committee concluded that the E-ELT project’s baseline cost, contingency and schedule planning is ready for the project to proceed to the construction phase.

The committee strongly endorsed the approach of FEED contracts as a way of reducing the cost risk on the project — whereby qualified companies have been paid to perform design studies, at the end of which they provide a contractually binding offer that is one customer signature away from an executed firm fixed-price contract.

39-metre Telescope Concept

The optical design of the telescope is that of a three-mirror anastigmat used within a small field about its axis. Two folding flats are used to extract the beam to a Nasmyth focus. The f/0.88 elliptical primary mirror (M1, conic -0.996) has a diameter of approximately 39 metres and an 11-metre central obstruction. The 4.1-metre secondary mirror (M2) is convex and returns the beam, through a hole in the quaternary mirror (M4), to the 3.7-metre mildly aspheric concave tertiary mirror (M3) located at the vertex of the primary. The beam is reflected to the 2.4-metre quaternary flat adaptive mirror that is inclined at 7.7 degrees to the beam direction. The fifth mirror (M5) in the train is flat, elliptical in contour (2.6 metres x 2.1 metres), defines the altitude axis of the telescope, and steers the beam towards the Nasmyth focus. The output beam at f/17.5 is very nearly diffraction-limited over the entire ten-arcminute field of view.

The f/17.5 beam can be redirected through relay optics to a coudé focus provided within telescope foundations at the ground level.

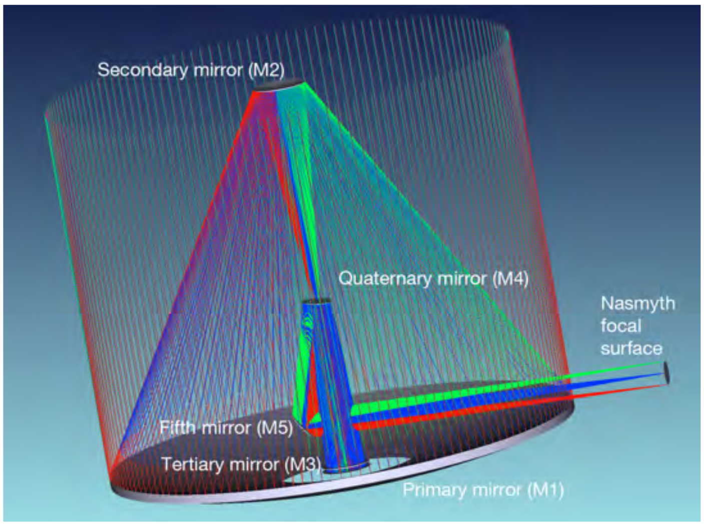

Figure 7. Optical layout for the Nasmyth configuration of the E-ELT.

The optics are mounted on an altitude–azimuth telescope main structure that uses the rocking-chair concept with two massive cradles for the elevation motions and two major azimuth tracks. The structure weighs approximately 3000 tonnes. In the central obstruction of the primary a 10-metre-tall tower supports the quaternary and M5 mirrors.

The Instrumentation Plan

The instrumentation plan for the E-ELT follows on from the 11 design studies developed during the period 2007–2010. The design studies provided an excellent pool of instruments that addressed the broad spectrum of capabilities necessary to attack the E-ELT science goals.

The instrumentation plan is motivated and bound by a wish to deploy cutting-edge instrumentation on the telescope as early as possible without blocking early scientific access to the telescope by excessive commissioning and debugging.

Two instrument concepts have been selected for the first light complement of the telescope: a high spatial resolution multi-conjugate adaptive-optics-assisted camera/spectrograph and an adaptive-optics-assisted integral field spectrograph. These instruments will be mounted on the Nasmyth foci of the telescope. An instrumentation roadmap has been produced that identifies instruments three through five plus the pivotal planetary camera/spectrograph, and identifies the key decision points in their construction. The instruments to be mounted on the telescope after first light will start their design and prototyping activities during the period of construction.

The operations budget for the observatory includes of order 20 M€ per annum for investments in new facilities for the E-ELT, of which some 9 M€ per annum is for an ambitious instrumentation programme.

The Management Plan

The management of the E-ELT design project is geared to evolve naturally into the construction project. With this in mind, the project office is structured to lead the core decision and control areas of the project while sourcing almost all the manpower resources necessary to follow the contracts and any developments from the matrixed and service divisions of ESO.

Such a lean project office does not carry excessive overheads and provides the ESO management with the flexibility to prioritise activities without an increase in personnel. The E-ELT project will be executed from within the Directorate of Programmes by a dedicated E-ELT Division.

Led by a project manager reporting to the Director of Programmes and with direct access to the Director General, the E-ELT has a project controller, a project scientist, a project engineer, a systems scientist and a systems engineer following the different aspects of the activities, and lead engineers in the areas of dome and main structure, optomechanics, control, civil/infrastructure, operations and instrumentation.

Cost and schedule control follows the cost-to-completion and full-cost accounting principles that have guided the VLT and ALMA projects.

Project reporting follows the norms that ESO has established for all significant activities with a biannual report to the Finance Committee and Council.

Design Process

During phase B, the project initiated a top-down process using the input top-level requirements from the project scientist. In parallel, it launched industrial studies based on requirements extracted from the baseline reference design established at the beginning of the phase B. ESO engineers and scientists form a knowledge base that has a good understanding of telescopes and the assembled team was heavily involved in the VLT. The preliminary design requirements of subsystems were established and documented very early and industrial contracts were launched very soon after the start of phase B.

The subsystem breakdown has been largely conventional, relying on the VLT and other telescope experience within ESO. Five major areas were considered: dome and main structure; optomechanics; infrastructure and site; control system and system engineering. The project structured its management according to this breakdown, with lead engineers in each area. The detailed work breakdown structure followed product lines, in part avoiding allocation of resources in areas without direct output into the E-ELT project. For each subsystem, three stages of design have been considered.

Phase A design has been conceptual. The functionality of the system was shown, potential solutions were established and volume/weight envelopes set up. This was considered the minimum level of design necessary to advance from phase A to phase B.

Phase B1 design was a preliminary level design of the subsystem undertaken by an industrial partner. It was based on requirements generated by the phase A concepts. A phase B1 design shows the major components of the system and demonstrates, by analysis, that performance can be met. Mass and volume budgets were established. Interfaces to other subsystems were established and plausible cost estimates from industry evaluated. The phase B1 design output includes a thorough revision of the requirements and the technical specification for a next stage of the design.

Phase B2 design stage, referred to as the Front End Engineering Design, is a detailed design stage. FEED studies were undertaken by industry based on the requirements determined by the earlier design stages. FEED detailed design output is considered to be sufficient to tender for construction contracts. Construction will include some degree of final design work to move from the FEED level to shop drawings.

The phase B activities have delivered phase B2/FEED level designs for most of the critical subsystems.

The top-down approach, started in parallel with the design activities, has been coordinated by system engineering.

In moving from the 42-metre to the 39-metre design, the project has concentrated its resources on risk mitigation and cost reduction elements. As is described below, the dome, main structure, secondary and quaternary mirrors have been the focus of the extended phase B. Delta-FEED contracts or updates to designs have been undertaken during this period, resulting in a revised overall design. A major task has been to revise all interfaces based on the 39-metre baseline.

Phase B Industrial Contractual Activities

As a preamble, all contracting at ESO is undertaken through the procurement department and, as a norm, all work is tendered for. With very few exceptions, no work is directly sourced to a particular supplier. The procurement of the design work during the phases A and B has followed these rules. There is no binding commitment between ESO and any of the suppliers of design activity for further procurement. With a few exceptions, allowed within the procurement rules, ESO owns the intellectual property of the designs and every effort has been made not to commit to designs that are bound to particular suppliers.

During 2007, the E-ELT dome was the subject of two 500 thousand euro (500 k€) preliminary design (B1) contracts, with ARUP (UK) and IDOM (Spain) respectively, delivering a design and cost/schedule estimates for the procurement. A consolidation phase in 2008 followed in which further analysis in covering mechanisms and airflow issues were considered for one of the designs. The technical specification for the dome was updated to take into consideration the input from the preliminary design phase, and two FEED contracts (B2) were awarded in mid-2009 with IDOM (Spain) and EIE/Cimolai (Italy). The two 1.25 M€ FEED contracts are framed in such a way that a detailed design and construction planning as well as detailed cost estimates are provided. Binding offers to construct are also deliverables of these contracts. For the 39-metre design, contracts were placed with the FEED awardees to update the design and schedule/costs.

Wind tunnel and Computational Fluid Dynamics (CFD) analysis is included in the dome contracts. In addition to that work, the project contracted IDOM to evaluate further the interactions of the telescope and dome in the wind tunnel facilities of a subcontractor in the UK. The 39-metre dome has also been evaluated in the wind tunnel in the UK. The CFD results from the preliminary designs was analysed and further elaborated upon by Weatherpark (Austria). Additional analysis of wind tunnel data was undertaken by CIRA (Italy).

The independent review of the requirements and output (including costs) from the 42-metre FEED contractors was contracted to ARUP (UK) and DSL (Canada).

During 2007, the main structure was the subject of two 500 k€ preliminary design (B1) contracts with EIE/Tomelleri (Italy) and MTM (Germany) respectively, delivering a design and cost/schedule estimates for the procurement. During the consolidation phase, the MTM (Germany) design was selected as a baseline and some further work was undertaken to update the design to match the revised interfaces. The revised preliminary design was used to update the technical specifications of the main structure that were the basis for the tendering and eventual award of a single 1.25 M€ FEED contract to Empresarios Agrupados (EAI, Spain) in mid-2009. A delta-phase B contract for 800 k€ was placed with EAI for the update of the design to the 39-metre baseline.

An independent review of the requirements for the main structure and dome and output of the FEEDs (including costs) was contracted to DSL (Canada).

An independent review of the output of the delta FEEDs (including costs) for the dome and main structure was contracted to ARUP (UK).

DSL (Canada) and DEMONT (Italy) were contracted to evaluate the feasibility and scheduling of the construction and to provide possible optimisation scenarios. Analysis of the ESO handling needs was contracted to Solving (Finland), and an option for a total access platform to Bronto Skylift (Finland).

In mid-2007, two FEED-level prototype quaternary adaptive mirror unit contracts were awarded to CILAS/AMOS/Onera (France/Belgium) and ADS/Microgate/Sagem (Italy/France). Although launched as soon as realistically possible after phase B approval, their specifications had been validated through industrial studies undertaken with CILAS, Sagem and ADS/Microgate during phase A. These were 5.2 M€ contracts to include the construction of prototypes and firm fixed offers to build the final production units. As a risk mitigation activity, additional work was contracted with ADS/Microgate/Sagem for the study of the reference body and no-leak cooling options.

Also in 2007, the M5 electromechanical tip-tilt unit was contracted for 1.2 M€ at FEED-level to NTE/CSEM/Sagem (Spain/Switzerland/France). This included the delivery of a scale-one prototype. The contractor has studied a silicon carbide (SiC) mirror in collaboration with Boostec (France) for the M5. In parallel the project has undertaken conceptual design studies with ITT (USA) and Schott (Germany) for the provision of glass mirrors. With support from BCD (Italy) in the area of finite element model generation, a second heavy M5 study has been contracted to NTE/CSEM/Sagem. A small prototyping activity into SiC by Boostec/Sagem is being monitored by ESO as part of our risk mitigation activities.

In early 2008, two 5 M€ contracts were placed with Sagem (France) and Optic Technium (UK), since renamed to Optic Glyndwr, for the provision of seven aspheric prototype segments for the primary mirror. These FEED-level contracts culminated in firm fixed price offers to build the entire supply of segments needed for the E-ELT. These contracts include test setups and the necessary tooling and process development for the polishing. Three materials were selected for pairs of blanks, Schott Zerodur (Germany), Corning ULE (USA) and LZOS Astrosital (Russia). The seventh blank has been left free to the supplier to select. Optic Glyndwr has selected ClearCeram from Ohara (Japan) while Sagem chose Zerodur from Schott. In parallel the project has issued a contract for a production study for the primary mirror to ITT (USA). Additional risk mitigation contracts have been placed with Laboratoire d'Astrophysique Marseille (LAM) and Tinsley (USA) to stress polish segments.

In 2007, a 150 k€ contract was placed with CESA (Spain), with GranTeCan acting as a subcontractor, to establish a preliminary design of the segment support structure (connection to the main structure and whiffletree). Following this contract, a revision of the specification was made, taking into account the evolution of the design of the main structure and two FEED contracts for 750 k€ each were placed with TNO (Netherlands) and CESA (Spain) each for the design and construction of three segment support systems. The contracts include some handling equipment. These segment supports have been integrated with the polished mirrors at Sagem and influence function tests have been performed.

In mid-2009, two contracts for 150 k€ each were placed with Physik Instruments (Germany) and CESA (Spain) for the production of three prototype position actuators for the primary mirror units. A further study by Physik Instruments for mixed capability actuators has been included in the risk mitigation activities. At the same time one 150 k€ contract was placed with microEpsilon (Germany) for the production of a set of edge sensors for the primary mirror segments.

The airflow and cooling requirements for the primary mirror have been analysed under contract by Kirkholm (Denmark).

In 2008, a preliminary design (B1) 500 k€ contract was placed with MT Mechatronics (Germany) for the design of the secondary mirror cell. In parallel, an evaluation of the requirements and potential solutions for the entire secondary unit, including the mirror and polishing, was contracted to Brashear (USA). The outcome of these studies was used to call and award a 1.5 M€ FEED contract for the entire secondary unit (mirror polishing plus cell). This contract has been placed with Sagem/MTM (France/Germany) in late 2009 and has been amended to include the 39-metre secondary option. Design and production studies for the secondary mirror blank have been contracted to Schott (Germany) and Corning (USA).

In 2008 two contracts were awarded to AMOS (Belgium), namely the preliminary design of the pre-focal station at 500 k€ and the preliminary design of the tertiary cell at 300 k€. A further study of the prefocal station has been contracted to the Danish company Kirkholm. Additionally a 40 k€ contract was later awarded to AMOS/Micromega Dynamics (Belgium) to evaluate a prototype pneumatic shape actuator for the M3 unit.

Active Space Technologies (Portugal) have been contracted to deliver a preliminary design of the adaptive optics calibration unit.

In the area of the control system, contracts have been placed with Observatory Sciences Limited (UK) and SciSys (UK) for the evaluation of existing infrastructures, Rovsing (Denmark) and Critical Software (Portugal) for independent software verification and validation plans, Space Systems Finland (Finland) for the evaluation of real time requirements, the University of Liege (Belgium) for the control algorithms of the primary mirror cell and KN Systèmes (France) for the design of the primary mirror control system. The INES (Switzerland) has provided consultancy for the evaluation of the network requirements and control system demands. In addition, a contract with National Instruments (Germany) assisted with the solution of M1 and M4 control.

Alternate laser technologies based on semiconductors have been contracted to ORC (Finland).

For project control support, contracts have been placed with Franklin & Andrews (UK) for an evaluation of the project risk register, Threon (Germany) for support in the area of risk analysis and with ISQ (Portugal) for product assurance services. Specific support has been contracted to USB (Germany) for the configuration item data list generation.

Operations

The operations plan for the E-ELT observatory was one of the deliverables of Phase B. The plan has been revised to take into account the new telescope baseline, and aims at maximising the synergies between Paranal and Armazones, which will be operated as a single integrated observatory. The plan describes the operational concepts and plans needed to achieve the E-ELT Top Level Requirements, and covers aspects related to the observatory management, the science, technical, maintenance and logistic operations, the off-site development and support, the upgrade paths, the staffing requirements and the operations budget.

A number of principles inherited from the experience of operating the Paranal Observatory is at the core of the operations concept. The top-level goal is to maximise the scientific productivity of the

E-ELT. This is achieved by ensuring an optimal performance level of telescope and instrumentation by extensive use of metrology, as well as of preventive and predictive maintenance, where the most challenging goal will be to perform, within the available day-time hours, all the required maintenance and corrective tasks necessary to have a “ready-to-go” telescope at sunset.

There will be procedures designed to provide a safe, efficient and cost-effective operation of the facility to deliver scientific data of high and consistent quality together with all ancillary data needed for their calibration, and provide opportunities for technical upgrades and development of new instruments and Adaptive Optics (AO) systems over the lifetime of the facility.

The science operations are based on the VLT paradigm and will be fully integrated, both on-site and off-site, between the VLT and the E-ELT. Extensions taking advantage of technological developments (e.g., high bandwidth) will be implemented for the integrated observatory. The observatory will provide modalities of use of the facility adequate to the scientific goals of each project, and for the most part observations will be flexibly scheduled to make the best use of available atmospheric conditions. A calibration plan will be executed by the observatory to guarantee that scientific data can be calibrated up to a well-specified level of accuracy. The calibration plan will be the basis for monitoring the system performance by continuously monitoring selected parameters. All the science data obtained and their related calibrations will be stored in the ESO Science Archive, to ensure the long-term preservation and accessibility of the data to the entire scientific community through appropriate interfaces.

The operations plan identifies all the activities, both short term (e.g., daily exchange of two newly coated M1 segments) and long term (e.g., commissioning of new instruments), needed to carry out the above goals. Work plans have been defined for the technical operations, the inspections, the preventive, predictive and corrective maintenance of all subsystems of the observatory. The tracking of problems with the associated generation of work orders will be managed through appropriate software tools (an evolution of the current problem-reporting system and computerised maintenance management system in use at Paranal today).

Bottom-up estimates of the required time and manpower for each activity, based on the Paranal experience, have been used to determine the staffing (in terms of skills and numbers) and the cost of operating the E-ELT.

Conclusion

The E-ELT design phase has delivered a technically viable solution for an extremely large telescope built by industries and academic institutes in the Member States. The cost and engineering of the project has been validated through extensive interaction with industry and, to the extent possible, prototyping activities have bolstered the confidence of industry to be able to deliver the telescope components.

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