The European Extremely Large Telescope enclosure design

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Introduction

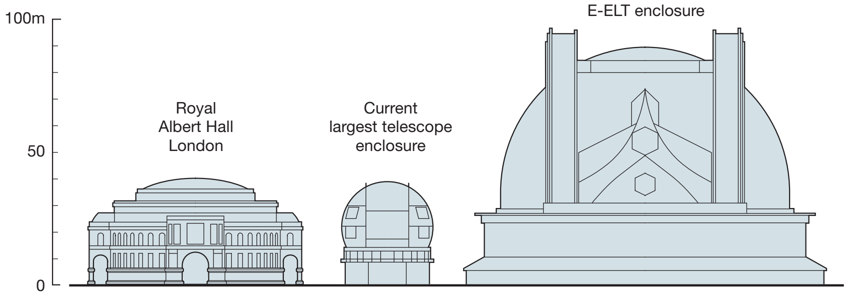
Modern astrophysics is tackling some fundamental questions. What was the origin of our universe? What will be its fate? Are we alone in the universe?

An important component in world-wide astrophysics strategy is the deployment of huge ground-based optical-infrared telescopes[1]. In the last quarter-century there has been a resurgence in large terrestrial telescopes, driven by the development of computer-controlled adaptive lenses that reduce the atmospheric distortion normally associated with ground-based telescopes. This technology, when applied to so-called Extremely Large Telescopes (ELTs), will vastly further astrophysical knowledge, allowing detailed studies of planets around other stars, the physical evidence of the earliest history of the universe, super-massive black holes, and the nature and distribution of the dark matter and dark energy that seem to dominate the universe.

Several ELT projects are currently being pursued around the world, including the Giant Magellan Telescope[2] and the Thirty Meter Telescope in North America[3]. Development of the European ELT (E-ELT) is being led by the European Southern Observatory (ESO). With a 42m diameter primary mirror, adaptive optics, and a large capacity for powerful post-focal instruments, the E-ELT (Fig 2) will offer image quality that is quite literally incredible - around 100 times better than that from the Hubble Space Telescope.

Arup was commissioned by ESO to develop a preliminary design for the E-ELT enclosure, the structure that houses the telescope (Fig 1). Drawing together a multidisciplinary team, Arup took advantage of its wide experience to develop innovative solutions to some of the unusual demands of the brief. These included a nesting door arrangement - unique among telescope enclosures and inspired by work on movable stadium roofs - and a novel design of crane.

> **"A telescope of this size could not be built without a complete rethinking of the way we make telescopes."**
>
> Catherine Cesarsky, former Director General of ESO.



1. Relative size of E-ELT enclosure.

ESO

ESO is the pre-eminent intergovernmental science and technology organisation in astronomy. It is funded by 13 European countries and has a remit to build and operate large astronomy facilities for use by European scientists.

Existing facilities include several telescopes around the 3.5m diameter range and the unprecedented array of four Very Large Telescopes in Paranal, Chile.

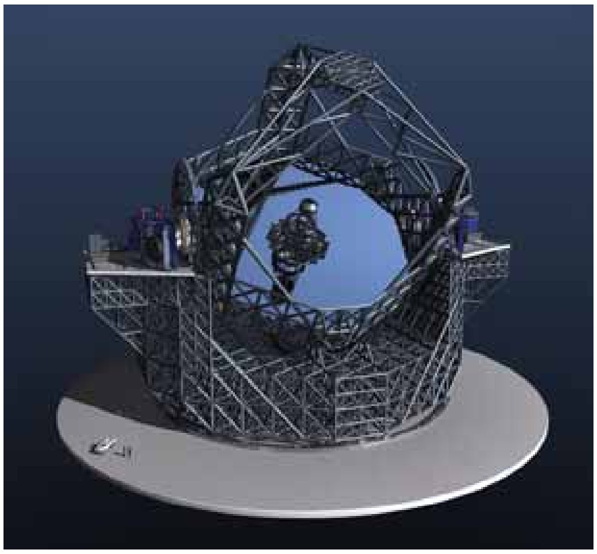
As well as the E-ELT project, ESO, in collaboration with North America, East Asia and Chile, is constructing an array of 66 antennae in the Atacama Desert, Chile for observation at sub-millimetre wavelengths.

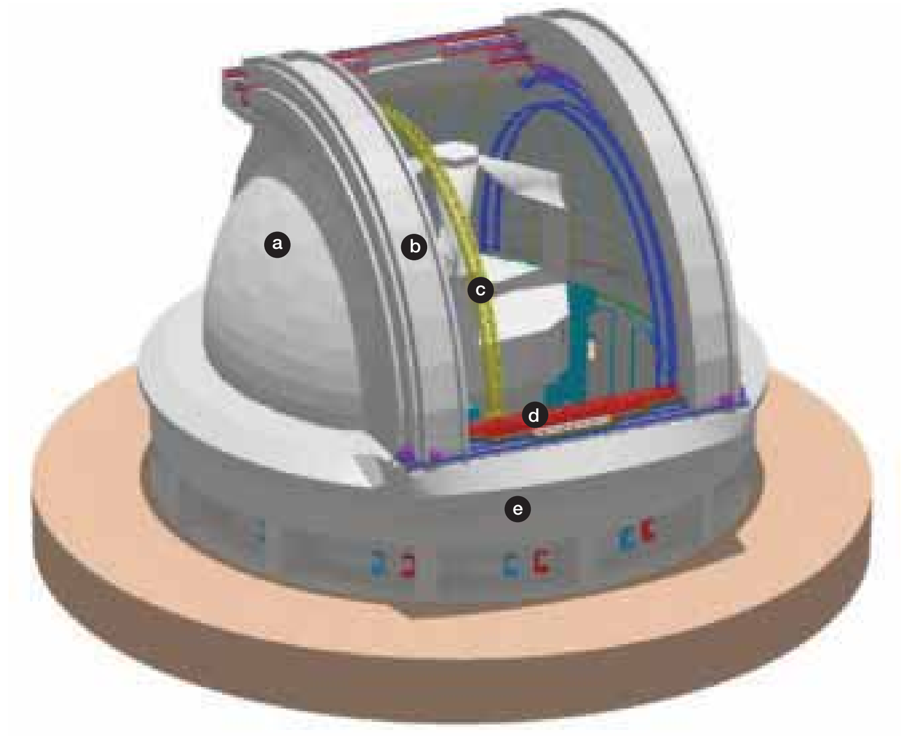
Purpose of the enclosure

The world's best sites for astronomical observations are at high altitudes (typically 2500-3000m above sea level), where the effects of atmospheric distortion are lower. As well as being difficult of access for construction, however, such sites form a harsh environment for telescopes, which therefore need to be protected by enclosures when not in use.

During the day the enclosure is closed and sealed in order to protect the telescope as much as possible from dirt and dust, the levels of which are far higher during the day than at night. This reduces the required frequency of cleaning the telescope mirrors, an expensive and time-consuming operation. The enclosure also closes to protect the telescope from adverse weather, like high winds or snow.

2. Artist's impression of the E-ELT. The telescope itself and its mount structure do not form part of Arup's design study.





3. Enclosure overview showing: (a) dome, (b) doors, (c) crane, (d) windshield, (e) concrete substructure.

4. Starfield in the central bulge of our galaxy, some 26 000 light years distant, photographed in 2006 by the Hubble Space Telescope. In this survey, called the Sagittarius Window Eclipsing Extrasolar Planet Search (SWEEPS), Hubble discovered 16 extra-solar planets by detecting the slight dimming of stars as the (Jupiter-sized) planets pass in front of them. The resolution of the E-ELT will be such that it will be able to observe such planets *directly.*

In addition to its protective function, the enclosure facilitates telescope maintenance. It provides access, and contains handling facilities for instruments, mirror segments, and other telescope components.

At night the enclosure must open to allow the telescope a clear view of the sky. In addition, it must minimise as much as possible image distortion, of which there are two main sources relevant to the enclosure. “Enclosure seeing” refers primarily to the distortion of the image due to thermal effects that affect the refractive index of air (an extreme version of this is the heat haze seen above roads on a hot day). If the enclosure releases significant heat into the air during observations, the warmed air may pass across the telescope’s line of sight causing image distortion. One approach to this problem is to completely remove the enclosure - for example roll it downwind of the telescope during observations - but that does not address the second role of the enclosure at night.

The image can suffer from telescope vibration due to wind buffeting, and so to enable its use in a greater range of conditions, on what are typically quite windy sites, the enclosure is used as a wind break to protect the telescope when winds are relatively strong.

Overview of the enclosure

The primary mirror of the E-ELT is supported in a steel frame that can be rotated about a horizontal axis, referred to as the “altitude axis”. This frame is in turn supported in a second steel structure, which can be rotated about the vertical axis, or “azimuth axis”. These two degrees of freedom allow the telescope to be pointed anywhere in the sky, typically 30° above the horizon.

Arup’s design for the E-ELT enclosure (Fig 3) comprises a steel-framed dome with a viewing slot covered by a set of arched doors that move on straight, horizontal tracks at the top and bottom of the slot and nest together in the open position. The dome is mounted on wheeled bogies running on circular tracks fixed on a concrete substructure. This enables the dome to rotate independently to the telescope structure about the azimuth axis, and helps minimise vibrations when the telescope tracks stars or planets. The dome rotation is usually carried out periodically through the night.

The enclosure houses a deployable windshield, which can partly cover the slot to protect the telescope during observations in high winds, and an arched, gantry crane and lifting platform for equipment handling. The enclosure is also clad with insulating panels, making it air, light and watertight, and is actively cooled during the day to maintain night-time temperatures inside, to minimise “enclosure seeing”.

Dome and doors

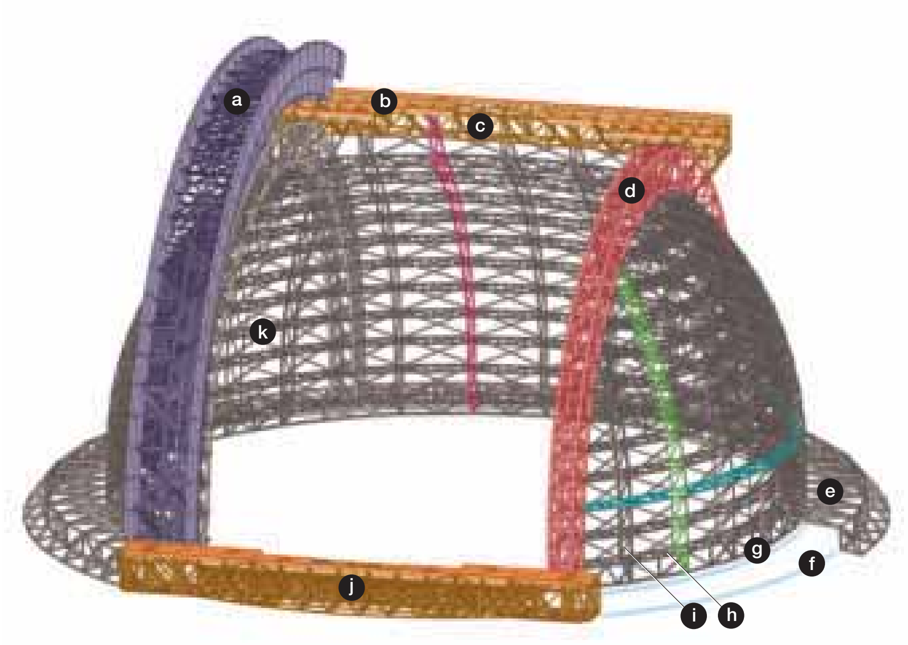
The dome is a hemispherical steel structure some 90m in diameter with a 45m-wide viewing slot running from the base of the dome to about 22.5m past the zenith (Fig 5).

Two rectangular box trusses form main arches that run along both sides of the viewing slot and span from the front to the back of the dome. Although the structure looks like a dome (and is referred to thus), its structural behaviour is rather different, due to the large relative size of the viewing slot. The dome sides behave structurally as shells, which under gravity “lean” towards the centre. This effect is countered partly by the lateral stiffness of the main trusses and partly by the shell behaviour of the sides, both resulting in large support reactions under the main arches.

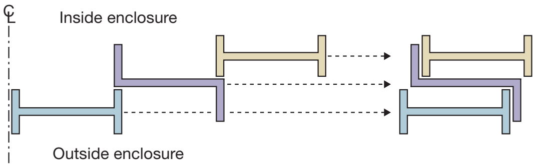
At the sides of the dome, vertical radial trusses extend from the circular track to the main arches at regular intervals. At the rear, between the main arches, vertical trusses with equal horizontal spacing run from the circular track to the viewing slot’s back edge, which is formed by the support structure for the upper tracks of the doors. The lower tracks of the doors are supported at the front edge of the viewing slot. This structure spans between bogies on the main circular track and a second concentric track, which has a radius some 10m larger. This second track is needed to carry the load of the doors which, when open, sit outside the main circular track by approximately 10m radial distance. Without the second track, the doors would have to be supported on some form of structure cantilevered from the main track, which would drastically increase the size of the lower track support structure and the loading on the bogies beneath it.

Horizontal trusses supporting walkways along the inside of the dome run around the structure and stop at the sides of the viewing slot. The frame formed by the horizontal and vertical elements is braced with diagonal members.

The arches together with the radials generate a radial thrust load which is taken by the bogies and in turn by the concrete base structure. The vertical and horizontal reactions at the tops of the doors are carried by the top track support structure and distributed to the bogies through the main arches and the vertical trusses at the back of the enclosure. At the bottom of the doors, the vertical reactions are taken by the front track support structure and distributed primarily into the outer circular track. Horizontal reactions at the bottom of the doors are carried to the main circular track further inwards. Because the doors act as an arch, their thrust loads increase the total horizontal reactions of the dome significantly.



5. Dome structure showing: (a) shutter panels, (b) panel tracks, (c) top track support, (d) main arch, (e) track cover, (f) offset track, (g) main track, (h) horizontal truss, (i) radial vertical truss, (j) front track support, (k) vertical truss back.



6. Section through nesting door arrangement in the open and closed position.

Six door panels, three on each side of the viewing slot, close the enclosure during daytime and in poor weather conditions. Each ca.8m wide panel spans from the front to the back edge of the viewing slot, running on horizontal tracks to allow it to move sideways. The shapes of these panels allow them to be packaged as close to the dome structure as possible. The pair with the largest span, and most distant from the dome, are central in the closed position. In horizontal cross-section, these are H-shaped. From the centre outwards, the next pair are Z-shaped, whilst the outermost – those that travel the shortest distance – are also H-shaped, allowing all six to nest when in the open position (Fig 6).

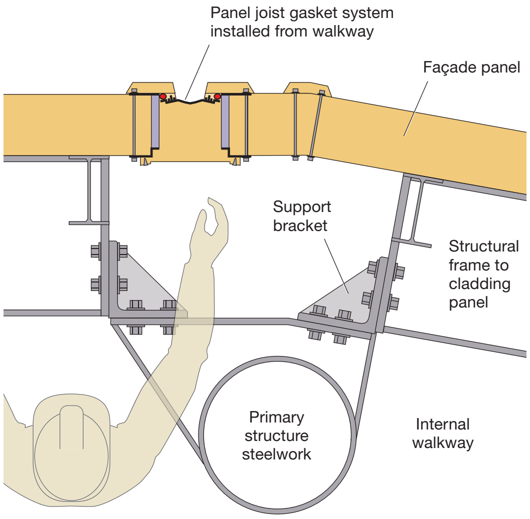
The design of the nesting arrangement of the doors draws on Arup’s experience of stadium roof design[4], achieving a more economic solution than would have been possible by simply scaling up existing telescope doors.

The panels’ structure consists of two deep plate sections on either side, and standard rolled steel sections to couple the plate sections and support the cladding. As previously noted, the panels arch between their supports so that both the vertical and the horizontal loads must be accommodated at the supports.

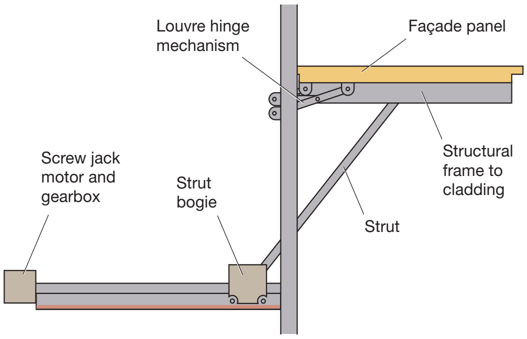
Façade

The façade panels must insulate the enclosure, allowing the temperature of the structures inside to be controlled so that when the enclosure is opened for viewing, heat release and consequent image distortion are minimised. The 150mm thick composite panels comprise a steel inner skin, insulating core material, and an aluminium outer skin. The latter is a client requirement; aluminium has suitable absorptivity and emissivity properties that reduce solar gain during the day and avoid excessive cooling of the façade at night by radiation to the sky.

The bays formed by the dome structure are all planar, so that flat façade panels can be used throughout. Each façade panel edge abuts those of its neighbours to create a sealed enclosure. Due to the scale of the enclosure and the exposed nature of the site, the composite panels would be assembled on site, at ground level, into larger, bay-sized façade panels, supported on a steel frame. The largest size of prefabricated façade panel would be approximately 10m x 4m.

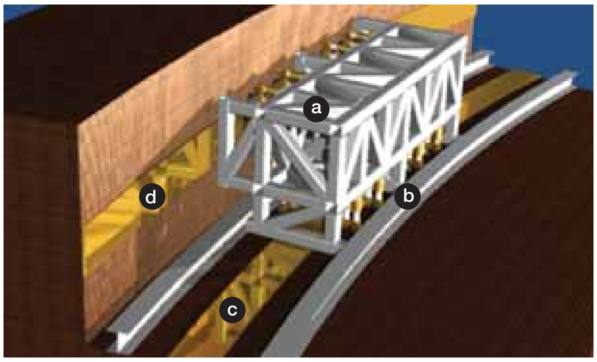


7. Typical panel joint.

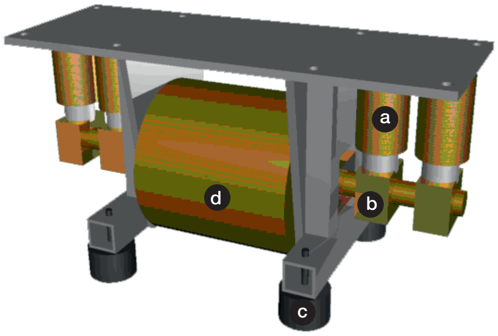


8. Ventilation louvres.

9. Typical enclosure support bogie showing: (a) bogie frame, (b) anti-uplift rail, (c) track for vertical loads, (d) track for lateral loads.



10. Roller module: (a) hydraulic jacks, (b) guided axle bearing, (c) guide rollers, (d) roller.



The panels at the sides of the enclosure are set out to a radial grid, which allows for repetition in their construction; apart from where they intersect with the main arches, horizontal panels will be similar to each other. This repetition will make the façade system easier to construct and simpler to install, with obvious cost benefits.

To allow the pre-assembled façade panels to be lifted more easily and in a wider range of wind conditions, Arup proposed a system of rails on the enclosure, to allow the large panels to be guided into position. This combination of ground level prefabrication and guidance system allows the façade to be installed in less time.

The prefabricated panels can be sealed together from the internal walkways of the enclosure using an EPDM (ethylene propylene diene monomer rubber) gasket. The panels cantilever beyond the primary structure, providing easy access to their joints (Fig 7).

The façade is perforated by about 100 opening louvres, each approximately 2m x 4m and independently actuated by a screw-jack to enable optimisation of the enclosure's ventilation at night (Fig 8). This is needed to ensure that the temperature of the telescope and enclosure structures tracks the ambient air temperature throughout the night, to reduce "enclosure seeing".

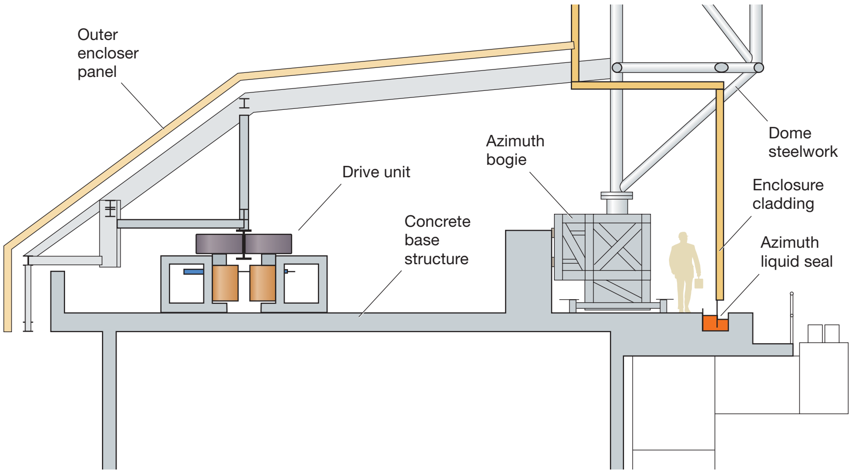
Azimuth mechanisms

Several drive units rotate the dome on its tracked wheeled bogies about the azimuth axis (Fig 9). The steel bogie frames distribute loads from the dome through a passive hydraulic system to up to eight steel rollers, four to carry vertical loads and four to carry thrust loads (Fig 10). The hydraulic system ensures even distribution of load between the rollers, and allows the reaction at each bogie location to be measured using a pressure transducer. The bogies are fitted with uplift protection to prevent them lifting significantly under extreme seismic or wind loading.

The space between the inner and outer circular tracks is covered with a skirt. The outer edge of this skirt is supported at regular intervals by a single roller module fixed directly to the skirt structure without any hydraulic load spreading (Fig 11).

The dome is driven about the azimuth axis by 48 drive units equally spaced in the area between the inner and outer circular tracks. The units are fixed to the concrete base structure and engage with a driving surface on the dome structure (Fig 12). Each unit consists of two sub-modules of a tyred wheel, driven by an electric motor mounted on a steel chassis connected to the concrete base structure by brass-lined sliders oriented to allow the chassis to move freely in the radial direction. The two sub-modules are clamped together by spring units so that in turn the tyres clamp the drive bar between them. The drive units are clustered in groups of four, and serviced by a power conditioning station supplied with electricity and cooling fluid to dissipate the heat generated during deceleration of the dome.

11. Section through azimuth drive and support zone at the perimeter.



The drive tyres are standard heavy truck tyres with an operational normal contact force of 40kN and a coefficient of friction at low speed of at least 0.25 in low temperatures without visible ice, and 0.6 on dry track at 20°C.

The telescope enclosure position will be read from an encoder mounted on the drive bar to return the aggregate position to within 0.5mm accuracy (+/- 0.0006°). The position will be confirmed by a further system of magnets fixed to the drive bar at 5m intervals, read by reed switches (electrical switches operated by an applied magnetic field).

The drive units are torque controlled, with an encoder on each axle to ensure that the wheels do not slip; the control system uses traction control algorithms to maximise traction and braking forces. The control system will operate the enclosure position to within +/-50mm for compatibility with viewing requirements.

The telescope enclosure and door structure is designed to withstand the ultimate loading conditions without the extra restraint of locking pins. Adding these could induce local loading into the structure and require the enclosure to stop precisely to enable the locking pins to be inserted. Instead of locking pins the enclosure utilises brake units that engage with the web of the drive bar. The clamp will only provide restraint in the direction of the drive bar.

Door mechanisms

A compact recirculating roller bearing system was chosen for the mechanisms that support the door panels at the top and bottom and allow them to be opened and closed along their straight horizontal tracks (Fig 13). This bearing is a commercially available product typically used for moving heavy structures. For the configuration in the chosen design, the supports could generate a drag load of up to approximately 5% of the support reactions during initial operations. This drag load reduces during the operational life of the door tracks and decreases the amount of power needed to open the doors.

Before opening the panels in snow or ice conditions, exposed tracks may require de-icing, either manually or through trace heating, to prevent additional load on the drive system. If trace heating is used the track sections outside the enclosure when it is closed would need to be heated.

As the door panels are tied arches, irregularities in the track could induce extra forces in the arch structure and supports. These loads were evaluated by performing a parametric analysis on the support conditions using Arup's GSA program, including altering connection stiffness and applying enforced displacements on the structure.

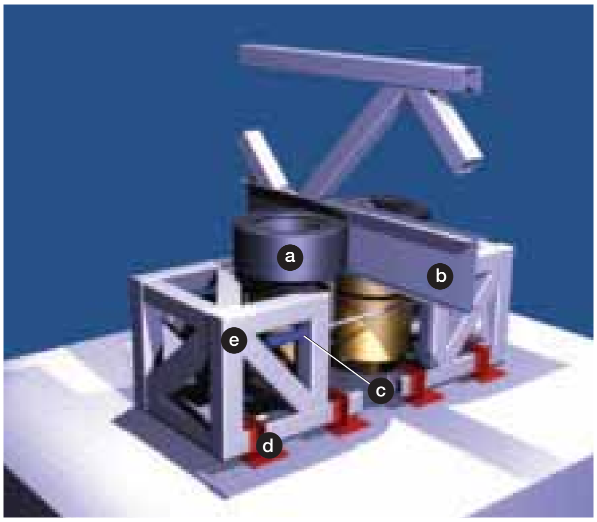
The drive mechanism for the doors has to overcome friction, wind loading, any residual ice and snow, and any sticking effects of seals – forces which combined indicate that the use of a simple rack-and-pinion drive would be beneficial. These drives will be located at the top and bottom of the door panels, so that each panel is driven from both ends simultaneously. 10m lengths of standard rack are bolted to a steel H-section, which is connected to the door track support structure. The rack is engaged by a pair of pinion drives, mounted on the door panel, which can generate up to 280kN thrust from a three-phase 45kW fan-cooled motor. Each door panel is supplied with power via a 70KW umbilical at the top and bottom locations.

The door panel locking mechanisms use a similar device to those used to hold the telescope enclosure against azimuth rotation. Each door panel requires a brake unit that can develop 500kN braking force at the top and bottom of the panel. Application of this lock will be carefully controlled by control systems so that the doors can be accurately parked. This is important for adequate sealing of them.

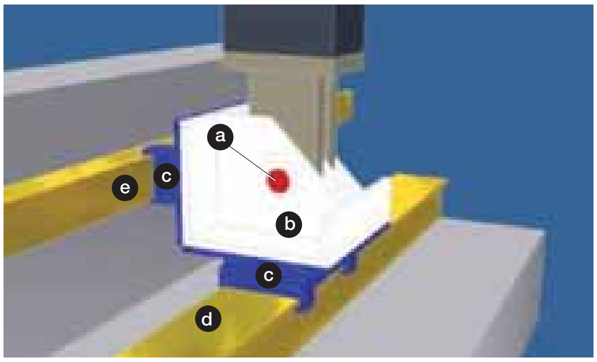
The base structure

The structure of the enclosure base follows from both the task of carrying the loads from the enclosure dome, and from some functionality requirements in the client's specification.

Vertical loadings from the steel enclosure are directly supported by an inner ring wall some 22m high above ground and extending 5m below ground. This is stabilised by 12 radial walls of the same vertical dimensions and radial width of around 10m.



12. Drive unit showing: (a) tyres, (b) drive bar, (c) spring unit, (d) sliding connectors, (e) drive chassis.



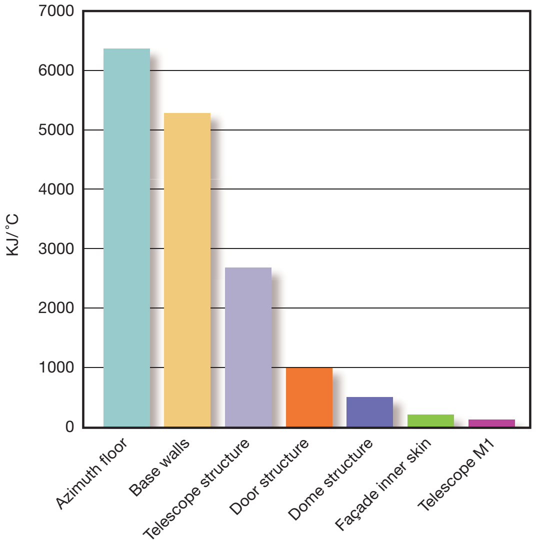
13. Door support bogie showing: (a) structural pin, (b) steel transfer structure, (c) re-circulating bearing, (d) track for vertical loads, (e) track for thrust loads.

Lateral loadings from the dome are transferred through a top slab into the inner ring wall and into the radial walls. The top slab is supported by a 10m deep beam, underneath the outer track, which also carries the vertical loads from the bogies under the door track support truss. Vertical and lateral loading from the structural elements is transferred into the ground by a bottom slab. Perpendicular ribs are added so as to reduce the sensitivity to buckling of the free outer edge of the radial wall.

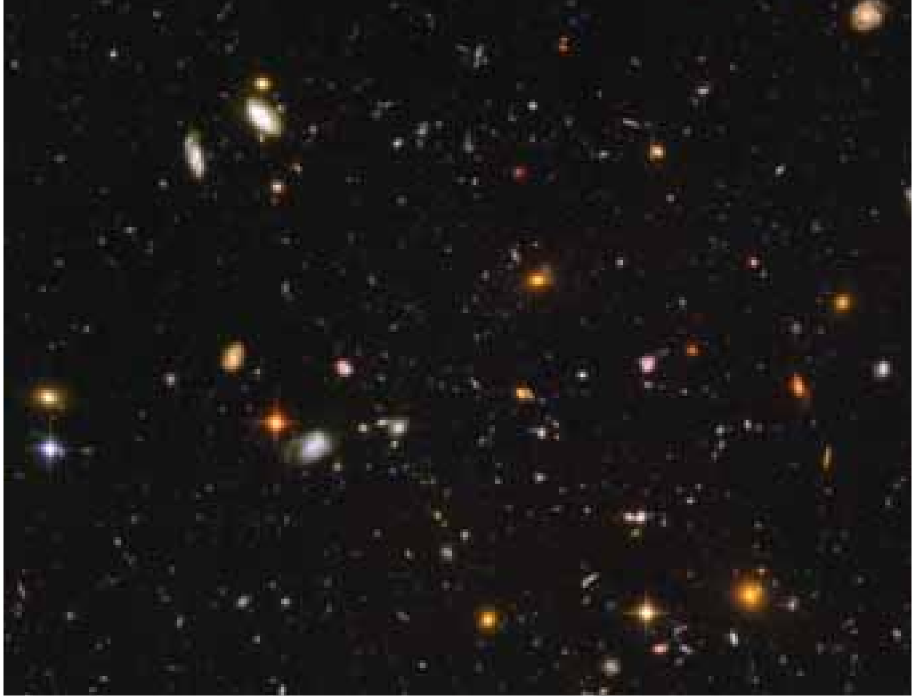
Thermal control

To minimise night-time release of heat into the air passing across the telescope's line of sight with resulting deterioration of image quality, the enclosure interior is actively cooled during the day. The aim is to maintain the temperature of the telescope and surrounding internal structures at the following night's predicted external temperature.

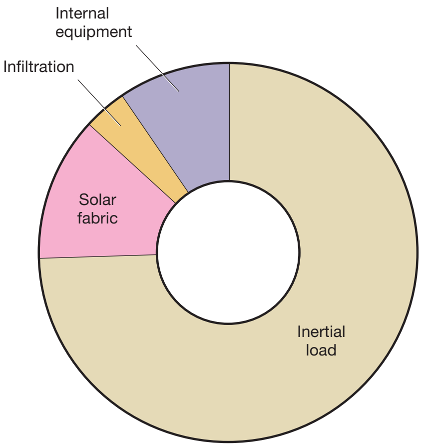
Variations in the temperature of air passing across the telescope around the enclosure can change the density and refractive index of the air, giving rise to optical distortions. If this occurs within the telescope's line of sight the effect can be detrimental to the quality of its seeing.



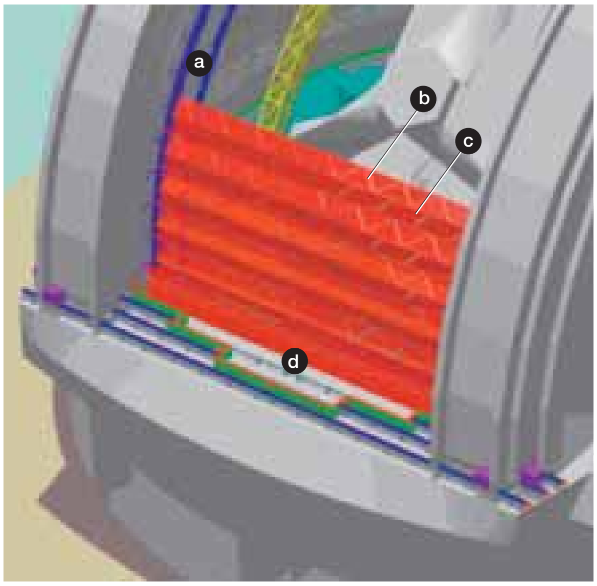
14. Thermal inertia of main enclosure systems.



17. E-ELT's resolution will enable it to "see" even further back into the early history of the universe than Hubble's most distant images, eg these galaxies only about 1bn years after the Big Bang.



15. Proportion of cooling load from different sources.



16. Windshield showing: (a) tracks on main arches, (b) hinged plane trusses, (c) fabric infill panels, (d) windshield retracting to space below telescopic sightline.

ESO's main design requirement for the cooling system required the temperature of all internal structures to be within 1°C of the external night-time temperature for a temperature difference between the inside and outside of the enclosure of 10°C. A secondary design requirement related to the advent of a cold weather front, ie the internal structures needed to be cooled to within 1°C of external temperature when it dropped by 10°C between the end of one night and the start of the next night.

The cooling system was therefore sized to remove heat from the following sources:

- solar gain of the enclosure
- warm air infiltrating the enclosure
- internal sources, eg motors, lights and people
- outside air deliberately introduced into the enclosure to provide a positive pressure in the enclosure volume
- thermal inertia of structures in the enclosure, eg telescope structure and enclosure steelwork (Fig 14).

Where possible, the large thermal masses in the enclosure are rendered inactive – by insulating the enclosure doors, the concrete walls, and floor. The telescope itself, being outside Arup's remit, is not insulated.

The total cooling load of 1405kW (Fig 15) gives a requirement for a volume flow rate of 290-320m³/sec, depending on the site altitude.

Air is supplied to the enclosure by 10 air-handling units through a series of three concentric ring ducts at the top and midway up the enclosure wall, and around the base of the telescope. These supply air to many nozzle units which jet cooled air over the telescope and the enclosure surfaces. Nozzles are used because they can supply cool air to the enclosure dome without the need to pass cooled air through ducts across the moving boundary between the dome and the enclosure base structure.

The windshield

During observations, the viewing slot can be partially covered by a deployable windshield (Fig 16) to protect the telescope from wind buffeting, which degrades the image. The windshield is a concertina, formed from a series of hinged plane trusses infilled with fabric to block the wind. These trusses are supported on yet another set of wheeled bogies, running on tracks fixed to the main arch.

When required, the windshield is lifted by cables running over the main arches to winches at the rear of the dome. When not in use, it folds below the telescope view into a space just inside the doors at the front of the dome. The windshield height can be adjusted when necessary throughout the night to provide maximum protection to the telescope without impinging on its view.

The handling facilities

The enclosure requires handling facilities for maintenance tasks, provided by an overhead crane and a lifting platform. The 20 tonne SWL (safe working load) crane will be used primarily for swapping out primary mirror segments for cleaning, but also to handle instruments around the secondary mirror and in the mast structure at the centre of the telescope.

The crane is of a novel arched gantry design (Fig 18) which, combined with a lifting range of 70m, allows loads to be hoisted from the azimuth floor and carried clear over the telescope working volume. When in use, the crane moves across the viewing slot on straight, level rails on the door track support structures, giving immediate access to much of the enclosure volume. By rotating the dome, on which the crane is mounted, the remaining enclosure volume can be accessed. During observations the crane parks against a main arch, out of view of the telescope.

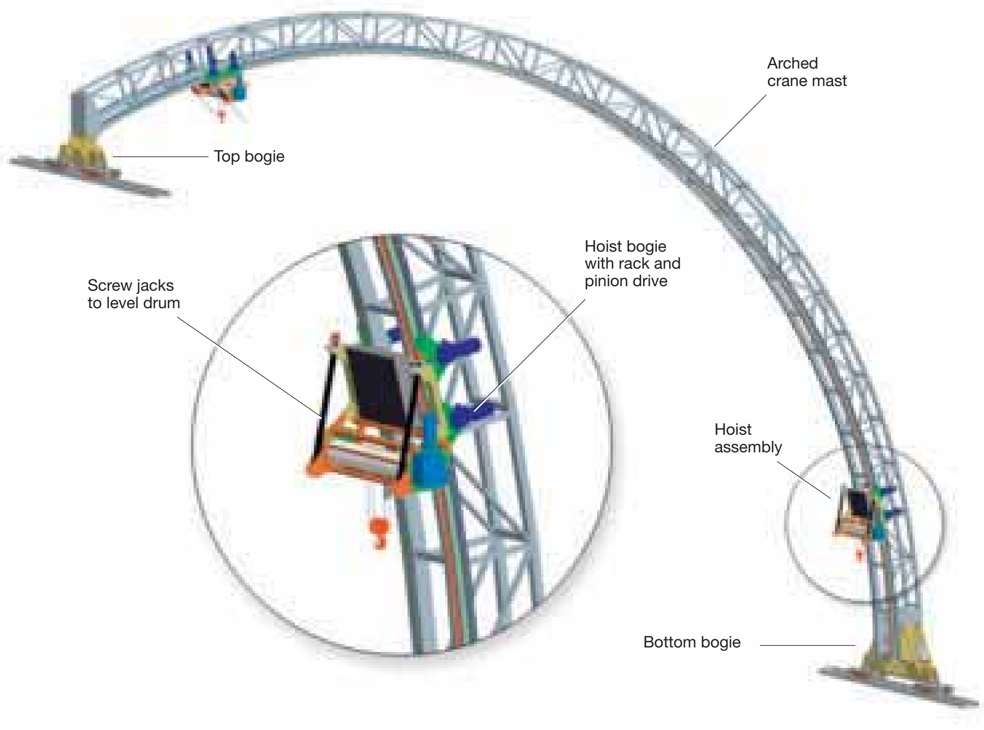
The 30 tonne SWL lifting platform (Fig 19) will be used to lift instruments from the azimuth floor to the 25m high Nasmyth platforms at the side of the primary mirror. As is characteristic of the Nasmyth type of reflecting telescope, the light beam is directed along the altitude axis into these instruments.

The lifting platform is horizontally constrained by bogies running on a pair of vertical rails fixed to the enclosure wall, and also counterbalanced with the additional lifting force provided by a pair of multi-stage, telescoping hydraulic actuators. When not in use the platform retracts level with the azimuth floor, the platform structure and actuators being accommodated in a 10m deep pit beneath.

The next steps

Arup's work formed part of the detailed design phase of the E-ELT, which began in December 2006 with the approval of the € 57m, three-year programme, and is ongoing with a further design iteration before tender. This will pave the way for beginning construction of the facility in 2010, provided that the necessary funding is secured. The target is for the E-ELT to be operational around 2017.

18. Novel arched crane design.



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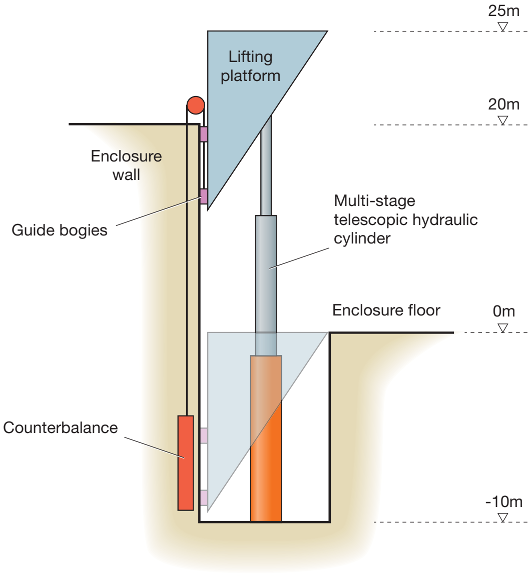
(4) CHAN, J, *et al*. Miller Park. *The Arup Journal*, *37*(1), pp24-33, 1/2002.



19. Lifting platform schematic.

Davar Abi-Zadeh is a Director of Arup in Building London Group 3. He designed the cooling and ventilation system for the E-ELT project.

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John Lyle is a Director of Arup with the Advanced Technology+Research London Group. He was Project Director for the E-ELT.

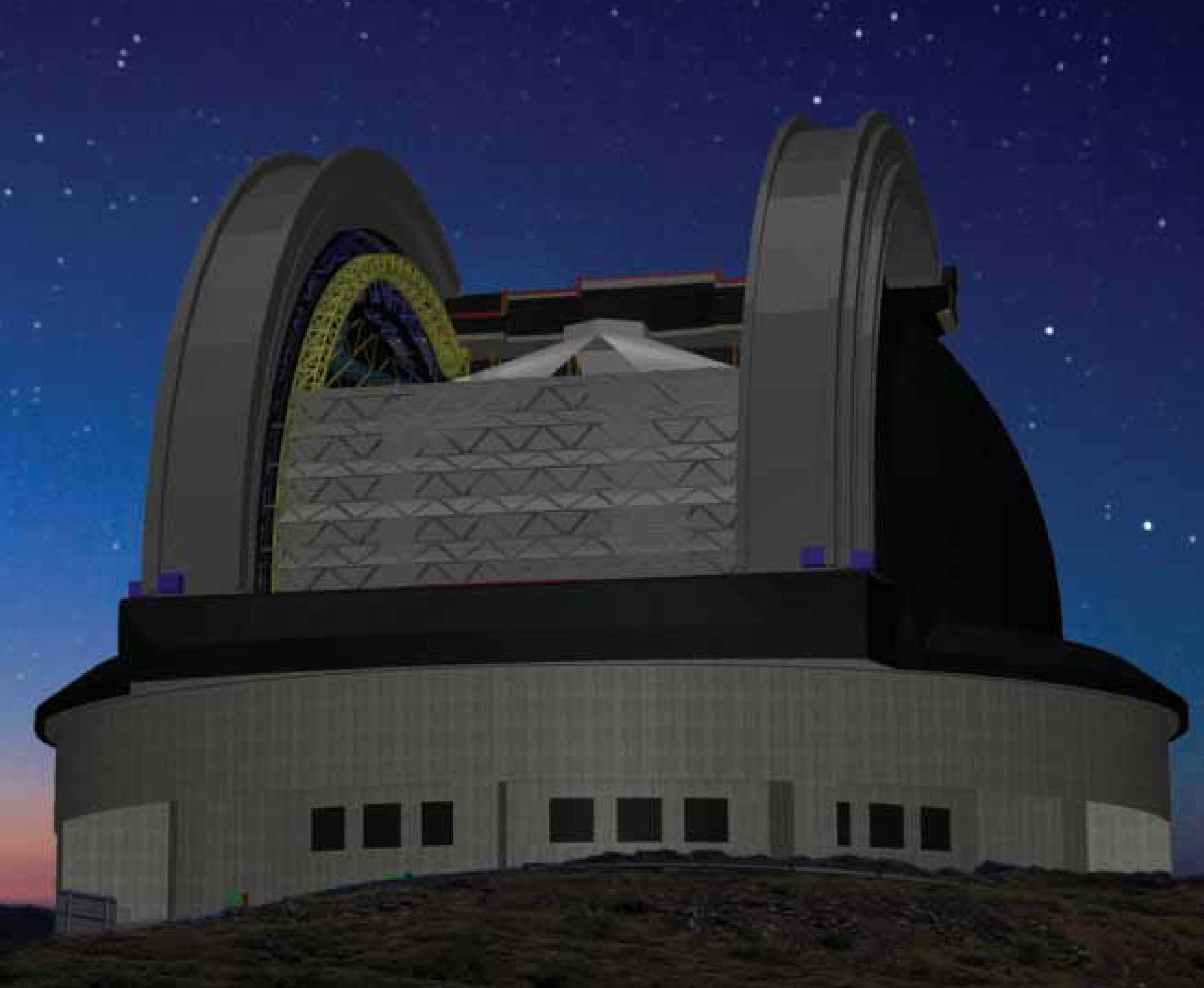
Pieter Moerland is a senior engineer in Arup's Düsseldorf office. He designed the project's concrete base structures.

Hugo Mulder is an engineer with Arup's Advanced Technology + Research London Group. He designed the dome and door structures.

Roland Trim is a senior engineer with Arup's Advanced Technology London Group. He designed the E-ELT enclosure's azimuth rotation mechanisms and door opening mechanisms.

Credits

Client: European Organisation for Astronomical Research in the Southern Hemisphere (ESO) **Architecture, SMEP, mechanisation, wind, control systems, and façade engineering, lighting and cost consulting:** Arup - Davar Abi-Zadeh, Pavlina Akritas, Andrew Allsop, Dan Bergsagel, Phil Brogan, Mike Clifton, Jac Cross, Graham Dodd, Christina Fell, Chris Fulford, Tony Greenfield, David Griffiths, Chris Harvey, Florence Lam, John Lyle, Daniel Meiner, Pieter Moerland, Strachan Mitchell, Hugo Mulder, Ender Ozkan, Dipesh Patel, Adam Pearce, Roland Trim, Felix Weber **Crane design:** Arup *and* SCX Ltd **Lifting platform design:** Arup *and* Weir Strachan & Henshaw **Illustrations:** 1, 6-8, 11, 14, 15, 19 Nigel Whale; 2 ©ESO; 3, 5, 9, 10, 12, 13, 16 Arup; 4 NASA, ESA and K Sahu (STScl); 17 NASA, ESA and N Pirzkal (STScl/ESA); 18 Daniel Pickard ©SCX Ltd; 20 Chris Fulford.



20. Graphical rendering of the E-ELT enclosure at site.

About Arup

Arup is a global organisation of designers, engineers, planners, and business consultants, founded in 1946 by Sir Ove Arup (1895-1988). It has a constantly evolving skills base, and works with local and international clients around the world.

Arup is owned by Trusts established for the benefit of its staff and for charitable purposes, with no external shareholders. This ownership structure, together with the core values set down by Sir Ove Arup, are fundamental to the way the firm is organised and operates.

Independence enables Arup to:

- shape its own direction and take a long-term view, unhampered by short-term pressures from external shareholders
- distribute its profits through reinvestment in learning, research and development, to staff through a global profit-sharing scheme, and by donation to charitable organisations.

Arup's core values drive a strong culture of sharing and collaboration.

All this results in:

- a dynamic working environment that inspires creativity and innovation
- a commitment to the environment and the communities where we work that defines our approach to work, to clients and collaborators, and to our own members
- robust professional and personal networks that are reinforced by positive policies on equality, fairness, staff mobility, and knowledge sharing
- the ability to grow organically by attracting and retaining the best and brightest individuals from around the world - and from a broad range of cultures - who share those core values and beliefs in social usefulness, sustainable development, and excellence in the quality of our work.

With this combination of global reach and a collaborative approach that is values-driven, Arup is uniquely positioned to fulfil its aim to shape a better world.