Spiral Galaxy Messier 83

THE EUROPEAN EXTREMELY LARGE TELESCOPE

The European Southern Observatory is developing a telescope that is more than four times larger than current optical telescopes and at least 100 times (two orders of magnitude) more sensitive than the Hubble Space Telescope. Professor Colin Cunningham is leading the UK programme and writes for *Ingenia* on the scale of the project, some of the challenges involved and why an Extremely Large Telescope is needed.

Astronomy is the most ancient science, for many centuries closely linked to religion and superstition, with priestly classes enhancing their reputation by predicting cosmic events such as eclipses. It was also very important for obtaining economic and military advantage, in anticipating the seasons for agriculture, and for navigation. Since Galileo's time, these considerations have declined and astronomy is now a quest to enhance humanity's understanding of its place in the universe. Astronomy also retains its spiritual value as a source of wonder and as an inspiration to young people to join a great scientific enterprise.

It is 400 years since Galileo pointed his new telescope at the night sky, and confirmed the Copernican model of the solar system by discovering the system of moons around Jupiter. As we celebrate this event, we are planning to build a new generation of giant optical and infrared telescopes of up to 42 m in diameter.

These Extremely Large Telescopes (ELTs) present engineers with significant challenges in the design of the optomechanical and control systems, including the huge dome, the near 1,000 mirror segments, the adaptive optics systems used to cancel out atmospheric effects and the instruments needed to analyse the light.

TELESCOPE EVOLUTION

Scientific progress in astronomy has always been enabled by technological innovation and engineering prowess. This can be traced back to the Neolithic stone circles, through the great mechanical measuring instruments of Tycho Brahe in the 16th century and Lipperhey's adoption of spectacle technology to construct the first optical telescope in 1608.

For the next 400 years, key inventions and concepts have led to new types of telescope and new discoveries. These have enabled us to understand that the Earth is not the centre of the solar system, and the Sun is just an ordinary star at the edge of an ordinary galaxy amongst billions of others, all expanding

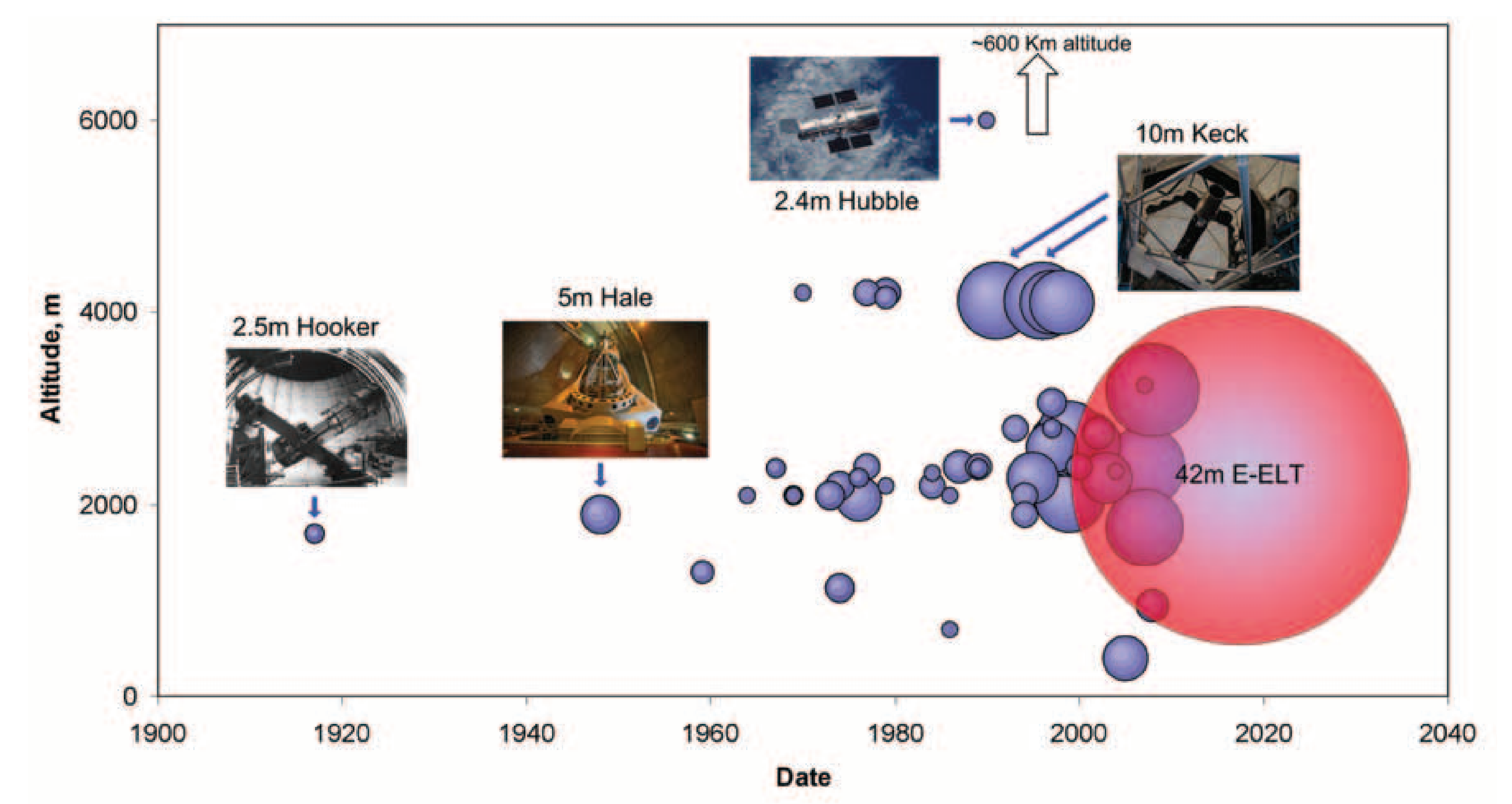


Figure 1. Comparing the European ELT with current 2-10 m optical telescopes. We have progressed from Galileo's simple telescope which had an objective lens of only 37mm in diameter to contemplating building a telescope with a primary mirror covering an area of over 1,300 square metres – about the same area as all the telescopes of more than 2m diameter built up to now © (left to right): The Archives, California Institute of Technology; Scott Kardel, Palomar Observatory; NASA & STScI; W M Keck Observatory

from the Big Bang. The acceleration of this expansion suggests the existence of dark energy, which, combined with the evidence of dark matter from galactic dynamics, means that it seems we can directly detect only 4% of the matter in the universe with our telescopes.

Telescopic innovation continued throughout the 20th century, and shows no sign of decline in the first decades of this century. Key technologies of the 20th century were computer controlled active structures and optics, segmented primary mirrors, highly efficient electronic detectors, and adaptive optics to remove much of the effect of atmospheric turbulence.

Today, there are 13 ground-based telescopes in the world with diameters from 8-10 m, plus several smaller space telescopes of which the most famous is the 2.4 m Hubble Space Telescope. This was recently joined in May 2009 by the biggest space telescope ever, the 3.5m Herschel Space Observatory, which will look at infrared radiation emitted by galaxies, stars, planets and comets.

Now the European Southern Observatory (ESO) is running a detailed design study for a 42 m European Extremely Large Telescope. The European ELT's 42 m diameter mirror should allow the study of the atmospheres of extrasolar planets. The E-ELT is currently going through a Phase B study that will end with a Final Design Review of the whole facility in 2010.

WHY BIGGER TELESCOPES ARE NEEDED

All the current large telescopes are very productive and in great demand, with up to six proposals for every successful observing programme. As well as finding evidence for the strange force that is accelerating the universe, astronomers have discovered over 300 planets outside our solar system and have even made the first direct images of giant self-luminous planets orbiting nearby stars.

Now astronomers want to reach further into the universe to find how stars and galaxies formed and to observe more detail in the images or spectra they detect. To do this, they need to collect more photons from the object they are observing by using a larger aperture telescope and to obtain higher spatial resolution, again by using a bigger telescope.

These objectives can be met by combining many smaller telescopes in an interferometer but in practice this has two disadvantages at optical wavelengths: sensitivity drops off as more telescopes are combined and the total field of view is limited to the point-source diffraction image size of each small telescope. As astronomers often want to study extended sources such as galaxies and star clusters, a large single mirror is preferred for most science goals.

ENGINEERING CHALLENGES

The design phase cost of €57 million for the novel five-mirror telescope is fully funded within the ESO budget. Industrial and academic teams across Europe have been mobilised to answer the primary design questions on how to build this ambitious telescope within reasonable bounds of cost and risk, whilst meeting the demanding requirements generated by the science teams.

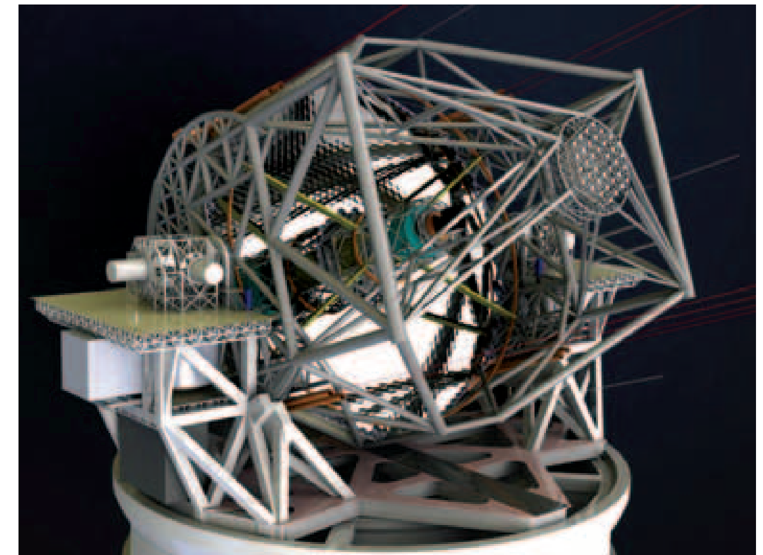
The critical engineering challenges to be addressed in designing and building this giant telescope are all to do with maintaining optical performance of the system in the face of perturbations. These are caused by the fluctuations of refractive index of the atmosphere, variable mechanical loads as the telescope slews round the sky to follow astronomical targets and mechanical disturbance caused by wind forces. There is also the added consideration of possible earthquakes to factor in, if one of the anticipated locations in Chile is chosen.

A space telescope has merely to focus the light from a distant star or galaxy onto a detector to form an image limited only by diffraction and the aberrations caused by static errors in the optical surfaces. A ground based telescope is more challenging, in that it needs to correct for the atmospheric disturbances that distort this image in a complex and time-variant way, and to maintain the optical quality of the mirrors in the face of perturbations due to wind and changes in orientation relative to the force of gravity.

The E-ELT primary mirror will need to maintain its surface shape to around 10 nm rms across its 42 m diameter – proportionally equivalent to limiting waves to 2 mm in height across the Atlantic Ocean. The E-ELT primary mirror will be made from 984 near-hexagonal segments, each 1.4 m across. The challenge of manufacturing these segments was the subject of a previous article in *Ingenia* 35 (Precision Surfaces, June 2008). Each of these segments will be supported by three actuators, and have sensors that enable its position to be maintained against gravitational and low-speed wind forces.

Two mirrors in the optical path to the focal plane (M3 and M4) will be used to correct for wind-shake and atmospheric turbulence (see below). This problem is particularly challenging for M4, the mirror being 2.6 m in diameter, only 2 mm thick and having 8,000 actuators operating at up to 1 kHz. This deformable mirror will be more than twice the diameter of any existing device.

Adaptive optics is critical to the success of the E-ELT. It is used to remove the fluctuations caused by the atmosphere



A CAD rendering of the European Extra-Large Telescope © ESO

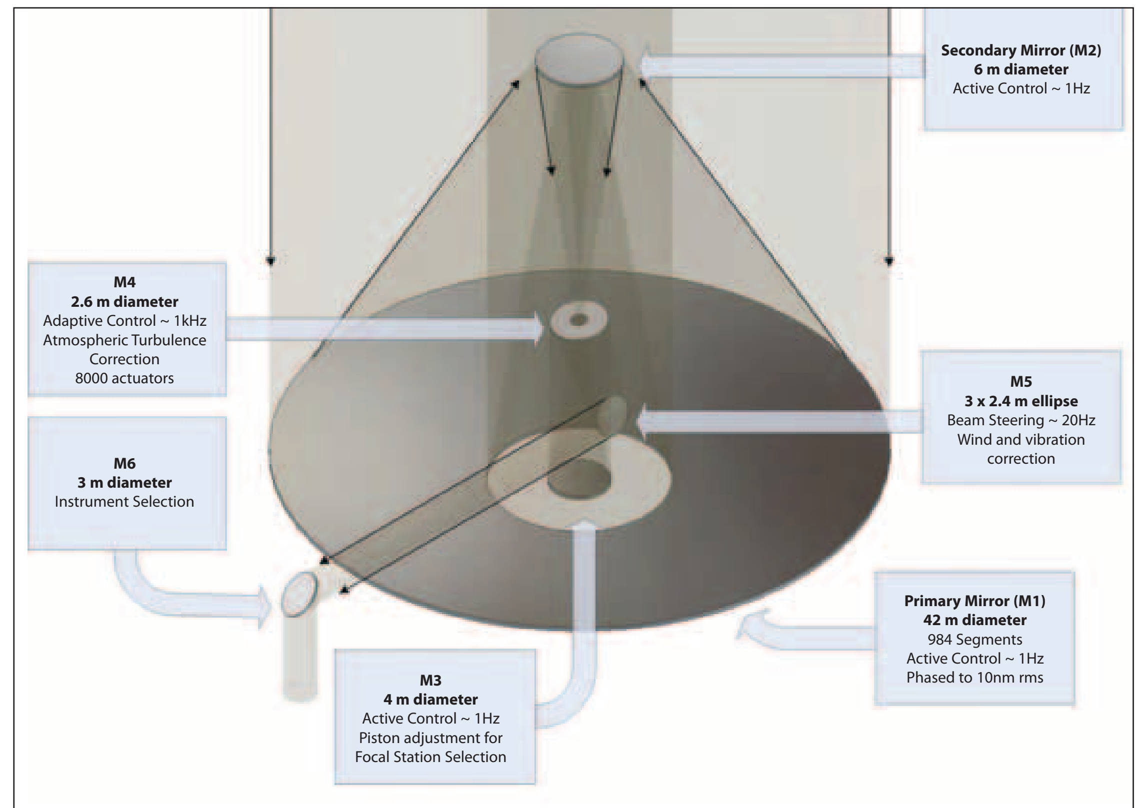


Figure 2. Optical Layout of the E-ELT. The E-ELT is a five-mirror anastigmatic design, optimised for image quality over a relatively wide field of view. It is a reflecting telescope whereby light falls on a concave primary mirror (M1), and is then reflected to a convex secondary mirror (M2). From here it enters the Adaptive Relay Unit consisting of three computer-controlled active and deformable mirrors (M3-5). The light then passes to one of two Nasmyth platforms that accommodate the instruments. Each platform is of about the size of a tennis court and can host up to four instruments

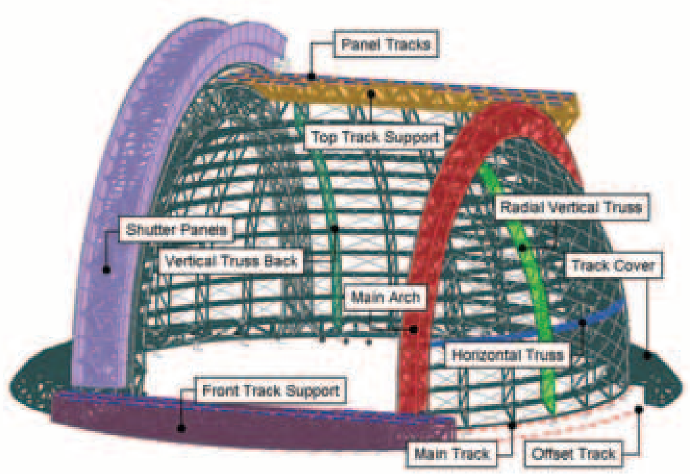
THE E-ELT ENCLOSURE

Two industrial contracts have been undertaken to develop outline designs for the enclosure. The one illustrated here is from Arup. When closed, the enclosure has to provide protection from adverse weather and dust, as well as keeping the telescope optics close to night-time operating temperature. The E-ELT will be mounted on a central concrete pier that ensures a minimum clearance of 10 m above the ground. This dome will have an approximate height of 90 m and a footprint of about 80 m diameter.

When in operation, it must rotate to follow the telescope, maintain stable airflow over the telescope and provide some attenuation of wind forces. It must also provide services such as handling equipment to enable replacement of mirror segments – at least one segment a day will need removal for re-coating to maintain optical performance. The enclosure design incorporates a horizontal sliding shutter arrangement comprising six panels that, in the open position, nest together on the outer edge of the enclosure opening, reducing the wind loading compared with more conventional dome doors. The majority of the primary enclosure structure is fabricated from standard structural steel sections.

To reduce construction costs, Arup minimised the need for a secondary structure by using standard long-spanning insulated cladding panels that attach directly to the primary structure.

The mechanisation of the azimuth rotation and shutter panels has been based on available technology. A maintenance-led design approach has been used to ensure these can be maintained easily and replaced if necessary without significant downtime.



which normally limit the angular resolution on the sky to about 0.5 arc seconds – whatever size telescope we use – equivalent to resolution of about 1 km on the Moon from the Earth at a wavelength of 1 µm. We can now produce images that are only limited by diffraction, at least at near infrared wavelengths. The size of a diffraction-limited image of a point source like a star is proportional to the inverse of the telescope aperture, meaning that a 42 m telescope could resolve 5 milli-arc seconds, equivalent to less than 10 m on the moon. Light from a distant science target arrives at the atmosphere as a plane wave, but is disturbed by the movement of cells of variable refractive index in the atmosphere. We measure the shape of this distorted wavefront by observing a known point source, such as a real star. However, there are not enough bright stars to enable us to correct all areas of the sky, so we also generate artificial guide stars by exciting sodium atoms in the upper atmosphere using powerful lasers operating at the 689 nm wavelength that excites the sodium atoms. Once we have measured the wavefront, we apply corrections using a deformable mirror to return the wavefront close to the flat surface it had before it entered the atmosphere. This results in a near-perfect corrected image. For an ELT, we need to use multiple lasers, 3D turbulence mapping techniques and multiple deformable mirrors to fully correct the whole column of air above the telescope.

CONSTRUCTION CHALLENGES

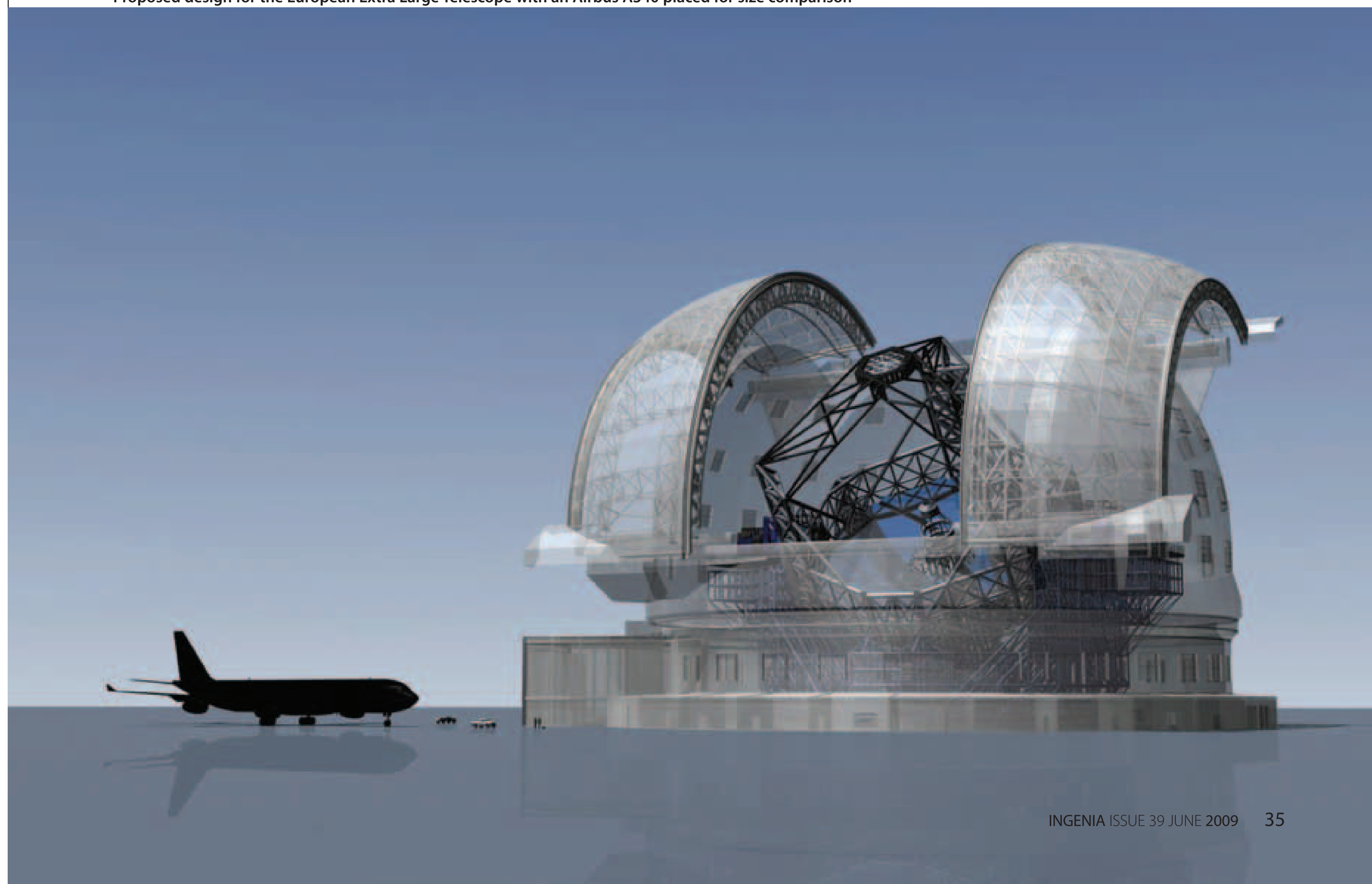
Most of the sites that are under consideration for hosting ELTs – typically in the high Chilean desert – are susceptible to earthquakes. A measure of the susceptibility of a structure to vibration is its lowest natural resonance frequency, which is inversely proportional to the square root of its mass. Current 8-10 m telescopes have a first resonance of 8 Hz, with a moving mass of around 200 tonnes. A structure as big and heavy as the E-ELT cannot be designed to be as rigid as a smaller telescope but clever use of Finite Element modelling has kept the first resonance above 2 Hz, despite the moving mass of nearly 5,000 tonnes.

Analysis indicates that mechanical amplification in the structure could result in accelerations of more than three times the normal gravitational force on critical optical assemblies. A precision telescope cannot incorporate permanent damping or isolating structures that would compromise its stiffness, so intelligent design of collapsible interfaces is needed to protect our billion euro investment, unless a site with low seismic activity is chosen.

With a telescope of this size, even the enclosure is challenging (see opposite). It has more in common with modern sports stadiums than existing telescope enclosures, given the huge opening doors needed to allow the telescope to view the sky. It is interesting that both of the industrial design studies commissioned on the enclosure came up with concepts very similar to the traditional dome shape, compared with current 8 m telescopes which often have more box-like structures.

Once the light from an astronomical target is focused by the telescope and adaptive optics systems, the job is still not complete. We have moved a long way from the days of relying on the human eye or photographic plates to interpret the images and spectra. Huge and complex instruments are needed to image and analyse the light electronically. Again, the challenge is to maintain image quality while analysing the light spectrally and spatially – this task being made all the more difficult by the need to cool infrared

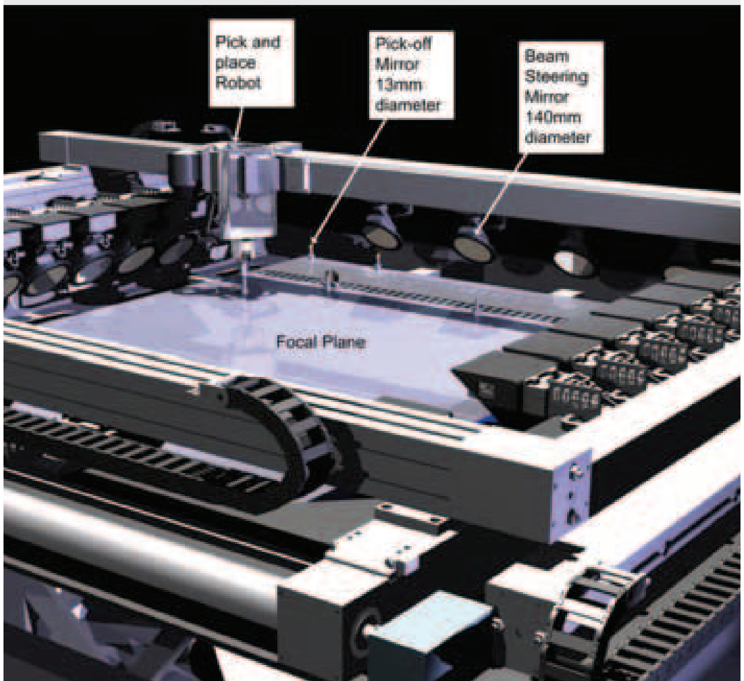
Proposed design for the European Extra Large Telescope with an Airbus A340 placed for size comparison



INSTRUMENTS FOR THE E-ELT

The telescope needs instruments to detect the photons and generate digital images and spectra. As might be expected, these instruments also present significant engineering challenges. A range of instrument concepts are being studied to address science problems, from detection and understanding of exoplanets, to imaging spectroscopy of galaxies in the early universe. The instruments cover a spectral range from 0.35 to 14 µm, spectral resolution (λ/Δλ) from a few tens to 150,000, and field of view from 1 arc second to 10 arc minutes.

An example of the technology challenges is shown here from the UK-French EAGLE concept. This instrument aims to improve the efficiency of the telescope by collecting and analysing infrared light from 20 galaxies simultaneously. The robotic target selection system is used to place pick-off mirrors on the focal plane of the instrument at the images of the galaxies. The beam steering mirrors relay these images to a set of imaging spectrometers. Each channel incorporates an adaptive optics system using a new technique called Multi-Object Adaptive Optics. The EAGLE instrument will enable dynamics of galaxies in the early universe to be studied, to help understand how they came to exist and how rapidly star formation occurred in them.



EAGLE robotic target selection system (UK ATC). UK groups working on instrument concepts for the E-ELT include the UK Astronomy Technology Centre, Durham University, Oxford University, and the Rutherford Appleton Laboratory

instruments to between 70 and 4 degrees Kelvin.

A particular challenge is provided by the need to obtain combined spectral and spatial information in order to build up 3D data cubes to understand galaxy dynamics in the early universe. This requires a combination of micro-optic image slicers and precision pick-off devices which we call Smart Focal Planes (as shown alongside). The UK is a world leader in these technologies, as well as in visible light detector arrays from E2V, and is gaining position in IR detectors from QinetiQ and Selex.

WHAT HAPPENS NEXT?

The E-ELT is going though an extensive detailed design, modelling, design validation, costing, risk analysis and prototyping phase. This will be completed by the end of 2010 in a proposal for construction. At that stage, the 14 ESO member states will be asked to approve the project. The construction cost is estimated to be €960 million (including first generation instruments).

Providing the necessary additional funds can be made available (perhaps with the addition of new partners), the telescope could start operation in 2018 at the earliest. Meanwhile, astronomers in North America are planning 22m and 30m telescopes on a similar timescale, so by the 2020s we can expect an enormous increase in telescope capability, heralding as huge a scientific leap as Galileo's telescope did in 1609.

Further reference

www.eso.org/sci/facilities/eelt
www.roe.ac.uk/elt/index.html
Stargazer: The Life and Times of the Telescope Fred Watson, Allen & Unwin (2004)
Electronic Imaging in Astronomy, Ian McLean, Springer Praxis Books (2008)

BIOGRAPHY – Colin Cunningham

Professor Colin Cunningham runs the UK Extremely Large Telescope Programme from the STFC's UK Astronomy Technology Centre at the Royal Observatory Edinburgh. A chartered Engineer and a Fellow of the IET, he has worked on astronomical instruments and systems for over twenty years. He was project manager of the first submillimetre camera, SCUBA, which was recently awarded a team achievement award by the Royal Astronomical Society. He chairs the OPTICON Framework 7 Key Technology Network, and is an Honorary Professor at Edinburgh and Heriot-Watt Universities, and an Honorary Senior Research Fellow at Glasgow University.