Precision engineering for astronomy: historical origins and the future revolution in ground-based astronomy

BY COLIN CUNNINGHAM1,* AND ADRIAN RUSSELL2

1 UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
2 European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching bei München, Germany

Since the dawn of civilization, the human race has pushed technology to the limit to study the heavens in ever-increasing detail. As astronomical instruments have evolved from those built by Tycho Brahe in the sixteenth century, through Galileo and Newton in the seventeenth, to the present day, astronomers have made ever more precise measurements. To do this, they have pushed the art and science of precision engineering to extremes. Some of the critical steps are described in the evolution of precision engineering from the first telescopes to the modern generation telescopes and ultra-sensitive instruments that need a combination of precision manufacturing, metrology and accurate positioning systems. In the future, precision-engineered technologies such as those emerging from the photonics industries may enable future progress in enhancing the capabilities of instruments, while potentially reducing the size and cost. In the modern era, there has been a revolution in astronomy leading to ever-increasing light-gathering capability. Today, the European Southern Observatory (ESO) is at the forefront of this revolution, building observatories on the ground that are set to transform our view of the universe. At an elevation of 5000 m in the Atacama Desert of northern Chile, the Atacama Large Millimetre/submillimetre Array (ALMA) is nearing completion. The ALMA is the most powerful radio observatory ever and is being built by a global partnership from Europe, North America and East Asia. In the optical/infrared part of the spectrum, the latest project for ESO is even more ambitious: the European Extremely Large Telescope, a giant 40 m class telescope that will also be located in Chile and which will give the most detailed view of the universe so far.

Keywords: precision; optics; telescopes; instruments

1. Introduction

The study of the heavens has driven the progress of engineering and technology from the beginnings of civilization. Progress in astronomy has been driven by practical needs as well as curiosity about our place in the universe. Governments

*Author for correspondence (colin.cunningham@stfc.ac.uk).

One contribution of 16 to a Discussion Meeting Issue ‘Ultra-precision engineering: from physics to manufacturing’.

3852 This journal is © 2012 The Royal Society
and leaders have funded astronomers for a range of motives. It is very likely that the ancient observatories like Stonehenge were designed for practical purposes such as predicting the seasons and celestial events for agricultural purposes as well as religious ones. The big stimulus for much of the history of astronomy was for astrology—that was why King Frederick of Denmark funded Tycho Brahe’s great observatory of Uraniborg on the island of Hven—a considerable investment at the time: Tycho said that it cost a ‘tun of gold’, most of which came from the king [1]. Of course, the major stimulus for astronomy for hundreds of years was for navigation—governments funded the national observatories such as the Royal Greenwich Observatory to enhance their command of the seas. However, astronomers over the years have always been primarily motivated to understand the universe.

The application of what is now thought of as precision engineering to develop telescopes and instrumentation can be traced right back to the early Fellows of the Royal Society, in particular Robert Hooke and Isaac Newton. Going further back in time to the end of the sixteenth century, Tycho Brahe was able to use his precision instruments to measure the positions of stars and planets to great accuracy even thought this was before the introduction of the telescope. Using the human eye and instruments such as the quadrant shown in the engraving.

Figure 1. Tycho’s quadrant, used to measure stellar position to a precision of $10^{-4}$. (Online version in colour.)
in figure 1, he was able to measure these positions to a precision of about 10 arcsec across the sky (effectively 1 part in $10^4$) certainly qualifying as some of the earliest high-precision measurements. Using Tycho’s data, Johannes Kepler was able to understand the motions of the planets and use this to formulate his laws of motion. This was a critical step towards Newton developing his universal laws of gravity—much more of an inspiration than the probably apocryphal tale of the falling apple. It can therefore be argued that the earliest precision measurement in astronomy directly led to the development of the science and engineering of mechanics, without which the scientific and industrial revolutions of the next centuries would have been impossible.

Since Tycho’s time, precision of measurement in astronomy has progressed by three orders of magnitude, with interferometers such as the European Southern Observatory’s Very Large Telescope Interferometer (VLTI) able to resolve 1 milliarcsec over 180° of the sky (1 part in $10^9$). To achieve this, the VLTI combines light from up to four 8 m telescopes or four 1.8 m telescopes with baselines of up to 200 m (figure 2).

This paper examines how this progression has been made over the last 400 years, and how the challenges in precision engineering have been overcome. The requirements of the next generation of giant telescopes and interferometers will push ultra-precision engineering into a new era.

2. The historical application of engineering skills to telescope building

(a) Optical elements and mechanical stability

Astronomy technology arguably started over 400 years ago with the adoption and development of the optical telescope for astronomy by Galileo [2]. Galileo’s telescope was a refracting telescope. If we compare the problems that had to be solved to make the first successful astronomical telescope with the challenges of building the next generation of giant telescopes such as the European Extremely
Large Telescope (E-ELT), there are clear parallels. The issues have always been manufacturing precision optical surfaces and maintaining the relative mechanical position of those surfaces—but of course the problems are on a vastly different scale. In 1609 Galileo [2] was able to improve the telescope that was invented in Holland about a year before to enable him to see the moons of Jupiter and thereby infer that Copernicus was right and the planets do rotate around the Sun. He was able to make these discoveries by improving the telescope by using better lenses and employing a technical trick to control the aberrations. Figure 3 shows a crude representation of one of Galileo’s telescopes. The telescope is a simple combination of a concave and convex lens with magnification given by the ratio of their focal lengths. The drawing identifies various parts of the telescope using the characters ‘a’ to ‘d’, but it is likely that the ‘o’ at the objective end is not an identification, but a representation of an aperture.

Some of Galileo’s lenses were measured by Vasco Ronchi in 1923 using his variant on the Foucault knife-edge test [3]. He showed them to have good figure near the centre, but to be poor at the edges. Introducing an aperture stop would therefore improve the optical performance considerably.

It seems likely that the breakthrough introduced by Lipperhey in the previous year was to stop the telescope objective down to around 1 cm [4,5], and Galileo took this forward with improved lenses to realize magnifications of up to 30 times, with good angular resolution. This illustrates that even in the early history of the telescope, overcoming defects in manufacture of optical elements was critical to success. Of course, Galileo had no knowledge of diffraction theory, so would not have known that for a perfect optical system, the angular resolution would be degraded by using an aperture stop. However, Robert Hooke, a few years later, seems to have understood this by carrying out experiments on better telescopes. This extract from *Micrographia* [6] indicates that he was able to see more stars in the Pleiades star cluster when he used larger objective stops:

> And indeed, for the discovery of small Stars, the bigger the aperture be, the better adapted is the Glass; for though perhaps it does make the several specks more radiant, and glaring, yet by that means, uniting more Rays very near to one point, it does make many of those radiant points conspicuous, which, by putting on a less aperture, may be found to vanish;

*Phil. Trans. R. Soc. A* (2012)
and therefore, both for the discovery of the fixt Star, and for finding the Satellites of Jupiter, before it be out of the day, or twilight, I always leave the Object-glass as clear without any aperture as I can, and have thereby been able to discover the Satellites a long while before; I was able to discern them, when the smaller apertures were put on; and at other times, to see multitudes of other smaller Stars, which a smaller aperture makes to disappear.

Galileo’s telescope was not improved upon for at least 30 years (for a full review see [7]). The next step was Kepler’s ‘astronomical telescope’, which used a convex eyepiece lens, providing larger field of view and hence easier use. However, it was more susceptible to lens defects, and required further improvement to lens manufacture. Once this challenge was overcome, it became clear that the limiting factor in image quality was chromatic aberration caused by changes in the refractive index of the glass with wavelength. It became clear that this could be overcome by using longer focal length lenses. Johannes Hevelius in what is now Poland took this literally to extreme lengths, eventually building a telescope 140 feet (42 m) long (figure 4).

Of course, a telescope of this length, supported by ropes and pulleys, introduced the next critical challenge for designers of large telescopes that persists until today—mechanical stability. Hevelius’s long telescopes would have been useless in the slightest wind, and aligning to astronomical targets would have been highly problematic.

Two solutions competed head-on until the early twentieth century. In 1672 James Gregory, a mathematician at St Andrews University in Scotland, designed a telescope that only used mirrors, so overcoming any image quality dependence on wavelength. Unfortunately, he could not find anyone who could make the
pair of concave paraboloid and ellipsoid mirrors he needed. Isaac Newton’s experiments with dispersion of light in prisms gave him a good insight into the problems of chromatism in refracting telescopes, and stimulated him to design a telescope with a spherical reflecting primary mirror and a plane mirror to send the light to a refracting eyepiece. Critically, Newton was able to make a good quality spherical mirror from ‘speculum’ (an alloy of copper and tin) using the technique of pitch-lap polishing that he invented and that is still in use today (figure 5).

Newton tested this telescope against a refracting telescope by attempting to read a copy of this journal [8]:

Yesterday I compared it with a six foot Telescope, and found it not only to magnifie more, but also more distinctly. And today I found, that I could read in one of the Philosophical Transactions, placed in the Sun’s light, at an hundred foot distance, and that at an hundred and twenty foot distance I could discern some of the words.

Meanwhile, Robert Hooke, who was the first Curator of Experiments at the Royal Society, developed new polishing methods, including a mechanical polishing machine, enabling him to make a Gregorian telescope in 1674—probably contributing to his life-long feud with Newton. The Gregorian design became dominant, particularly in commercial manufacture, with Edinburgh-born James Short selling over 1300 between 1734 and 1769.
The two alternative technologies—refracting and reflecting telescopes—remained in competition until the end of the nineteenth century. Glasses have always been easier to polish, and of course did not need to be re-polished to deal with tarnishing.

A solution to chromatic aberration in refractive telescopes was invented by Chester Moore Hall and marketed by John Dolland in 1758. He made an objective lens that used a combination of two different glasses (a doublet) to bring the focus of the different wavelengths of light closer together, leading to dominance of refractive telescopes until the problem of tarnishing of speculum was overcome by Foucault’s metal-on-glass mirrors. It is worth noting, however, that despite the chore of constant re-polishing, the giant reflecting telescopes of William Herschel and Lord Rosse were able to take advantage of their greater sensitivity and angular resolution to make key discoveries such as Uranus and the first detailed observations of the nebulae that we later came to realize were distant galaxies.

In 1895, the world’s largest refractor, the Yerkes Observatory 40-inch telescope, was completed. This, however, was the limit of what could be achieved by refractive optics since it is not possible to support lenses significantly larger than this. The next century was to become the age of the reflecting telescope.

Reflecting telescopes were able to far exceed the size of refractors because the primary mirror can be well supported from below in a stiff mirror cell and maintain the required surface figure accuracy of about 25 nm root mean square (r.m.s.). This is needed in order to ensure that the total wavefront error introduced by the telescope is less than one-twentieth of the wavelength of the light being collected, resulting in diffraction-limited images.

(b) Telescopes as smart structures

Over the last 10 years, the field of ‘smart structures’ has grown rapidly, but arguably the large reflecting telescope has been a pioneer of smart structures over at least 100 years. There are three main influences that perturb the shape and position of the optical surfaces: thermal, varying gravity and wind. Beyond the brute force approach of making the structure as stiff as possible and minimizing thermal coefficients of expansion, two main solutions have evolved over time as analysis and design techniques have become more sophisticated.

— Passive compensation. Using mechanisms or geometries that compensate for changes.
— Active compensation. Measuring errors and using active control of position or surface shape to compensate, either in closed-loop or by the use of look-up tables.

(i) Passive compensation

The problem of supporting large mirrors as the telescope tracks across the sky became more acute as apertures increased. The limitations of the brute force technique of attempting to make support structures as stiff as possible to avoid flexure of the mirror were soon realized. The Irishman Thomas Grubb and the Lancastrian William Lassell invented new solutions that could automatically compensate for variable forces acting on the mirror. Both used a rigid steel ‘mirror cell’, which was connected to the back of the mirror using mechanisms that
adjusted the supporting forces as the telescope tilted. Grubb adopted ‘whiffle trees’, as used for centuries to equalize forces in horse harnesses—shown in figure 6. Lassell used a system of levers to similar effect, and both these systems are still in use today. It could be argued that telescopes such as Rosse’s 1.8 m Leviathan of 1845 that used such passive compensation techniques were the first smart structures.

In 1948 George Ellery Hale’s crowning glory, the 200-inch Hale telescope at Mount Palomar, was completed (figure 7). Sadly, Hale did not live to see the telescope commissioned. Some 20 years after Hale secured a six million dollar grant from the Rockefeller Foundation, the telescope was dedicated and formally named in his honour. It was the largest aperture optical telescope from its completion in 1948 until the Russian BTA-6 was built in 1976, and the second-largest until the construction of the Keck 1 in 1993.

The Hale telescope is a perfect example of astronomy and technology. The design of telescopes at that time was what one might call ‘battleship technology’. Analysis techniques were limited and computer control of mirror supports did not exist; the structures had to be sufficiently stiff that the varying gravitational force did not destroy the delivered image quality as the telescope slewed around the sky. At the time, all the mirrors were so-called classical thick mirrors with an aspect ratio of about 6:1. This made the glass sufficiently stiff that it could easily be supported.

This kind of technology had been pioneered in Hale’s earlier telescopes, but the 200-inch exceeded the current state of the art. In order to keep the weight down to a manageable 14.5 tons, it was cast with a ribbed structure and with an overall thickness of some 24 inches (an aspect ratio of 8:1). This reduced the weight but reduced the stiffness and required a sophisticated passive mirror support system that balanced out the gravitational forces as the mirror tipped. Maintaining alignment between the primary and secondary mirror was also a
Critical challenge [9]. A young engineer called Marc Serrurier was recruited to the Hale design team, and he solved this problem. It was proving impossible to design a structure stiff enough to stop the mirror moving under variable loads without making it so heavy that it bent under its own weight. He realized that the important thing was not to attempt to stop all movement of the primary and secondary mirrors, but to keep them parallel to each other as the structure tracked around the sky to preserve the collimation of the telescope. By employing a dual truss structure designed asymmetrically so that the much heavier primary would deflect by the same amount as the lighter secondary, he was able to constrain those deflections to be parallel to each other (figure 8). Such truss structures became known as ‘Serrurier Struts’, and were the mainstay of telescope structural design until the advent of active structures. Serrurier went on to greater fame following his work with his father on the Moviola editing machine used by Hollywood film studios for most of the twentieth century, for which he won an Oscar.

The thin walls of the mirror also helped exceed the state of the art in another area: temperature stability. Its predecessor, the 100 inch suffered severely from temperature-dependent image quality. For the 200 inch, after spending a significant fraction of the total budget of the project on a failed attempt to make a mirror from fused quartz, Hale turned to Corning Glass to make the mirror from the newly developed low expansion Pyrex. This has a much lower coefficient of thermal expansion (CTE) than normal glass, and coupled with the light-weighting significantly improved the thermal performance of the telescope. Low-CTE mirror materials have since become standard on all modern telescopes.

The next step in the evolution of astronomy came in 1979 with the opening of the United Kingdom Infrared Telescope, UKIRT. This 3.8 m diameter mirror was originally conceived as a relatively inexpensive flux collector. It has a lightweight mirror with an aspect ratio of 16:1 and was not intended to produce high-quality images. However during the polishing of the primary mirror, the manufacturer,
Figure 8. The Serrurier truss structure on the Hale 200-inch telescope: (a) the original design concept drawing from 1937 showing how the primary and secondary mirrors stay in alignment, and (b) the truss structure in construction. Courtesy Scott Kardel, Caltech.

Grubb Parsons, offered to keep polishing on a best efforts basis and try to achieve a much better surface accuracy. This gamble paid off and more than 30 years later UKIRT is still doing world-class science. The thin mirror is supported by a pneumatic system and was upgraded in 1994 to a three-zone support system.

(ii) Active compensation

To some extent UKIRT’s performance was serendipitous, but the lightweight structure was to be the future of optical telescopes. The real paradigm change came though with the invention of active optics by Ray Wilson at the European Southern Observatory (ESO). Wilson’s idea was to make the primary mirror actively supported under closed-loop computer control, using signals derived from wavefront sensors looking at stars in the field of view of the telescope [10].

Across the globe astronomers and engineers were looking at how to solve the challenge of designing and building the next generation of telescopes. Jack Zirker provides an entertaining review of this story [11]. To make a significant advance in light-gathering power, it was deemed that primary mirrors of at least 8 m in diameter were needed. It was also clear that simply scaling existing technology would not work. The mass of an 8 m thick mirror would be prohibitive and require a huge structure to support it, plus it would have such a large thermal inertia that it would never reach equilibrium. This led to the need for a much thinner mirror. However, the deflection of a monolithic circular mirror under its own weight scales as $D^4/t^2$ (where $D$ is the diameter and $t$ is the thickness) so an 8 m diameter thin mirror would be very flexible. Three different solutions to this problem were pursued: the Keck 10 m telescope used a segmented mirror;
the ESO Very Large Telescope (VLT), Gemini and Subaru built large meniscus mirrors (typically weighing some 23 tonnes and with an aspect ratio of 50:1 [12]; and the Magellan Telescope used a relatively thick but massively light-weighted borosilicate mirror. All three solutions were successful and all three required the use of active optics. Modern 8 m class telescopes also have the following features in common: telescope mounts that move the optics in altitude and azimuth axes (alt-az mounts); highly optimized lightweight telescope structures; fast tip-tilt secondary mirrors; and complex thermal management systems.

As a technological class, they could be described as ‘aerospace technology’. The advances in computing and material technology that enabled the aerospace industry have also enabled modern telescopes. Without advanced finite-element analysis techniques, sophisticated computer control and complex system-level simulation capabilities, the leap to 8 m class telescopes would not have been possible.

(c) The La Silla Paranal Observatory

At the ESO, this next generation technology was prototyped on the 3.6 m New Technology Telescope (NTT) [13]. The NTT is an alt-az telescope with a relatively thin mirror (aspect ratio of 15:1). It was commissioned in 1989 and pioneered the use of active optics. At first light in March 1989, charge coupled device (CCD) frames were obtained on which stellar images had full-width half-maximum diameters of 0.33 arcsec indicating the excellent imaging quality of this telescope.

The telescope chamber is ventilated by a system of flaps, which optimize the airflow across the NTT minimizing the dome and mirror seeing. All motors in the telescope environment and hydraulic system are water-cooled to prevent heat input to the building. For the same reason, all the electronics boxes located on the telescope are insulated and cooled. The primary mirror is actively controlled with 75 actuators to preserve its figure at all telescope positions. The secondary mirror position is also actively controlled in three directions. The optimized airflow, the thermal controls and the active optics give the excellent image quality of the NTT.

This concept of prototyping for technology risk-mitigation is now fundamental to all big projects in astronomy and central to ESO’s strategy for new developments. Not only did the NTT demonstrate the new technology, it also became a test bed for the entire control system of the next ESO project, the VLT (figure 9).

The vision for the VLT was to produce a telescope with the effective collecting area of a 16 m telescope. Three solutions were studied including a single 16 m and four 8 m telescopes. In the end, four 8.2 m telescopes were commissioned at Paranal in Chile and are now recognized as the world’s paramount observatory.

(d) Sub-millimetre telescopes

Visible light or optical astronomy came first and was dominant for most of its history. But much of the light in the universe is emitted at other wavelengths. Modern astrophysics uses all the electromagnetic spectrum to study the universe. In many ways, the sub-millimetre region is the final frontier of astronomy because it has been so difficult technologically.
The millimetre/sub-millimetre region of the spectrum lies between the optical and the radio. Much of the detection technology is an extrapolation of techniques used in the radio regime. However, sub-millimetre telescopes use the same two mirror design as most optical telescopes. A sub-millimetre antenna must have a primary mirror (or a primary reflector as it is known in the radio-astronomy community) with a surface accuracy which is a fraction of a wavelength. To get useable efficiency at 350 mm wavelength, the surface r.m.s.e. must be about 25 mm or better. This immediately sets a size limit on the antenna due once again to the effects of gravity, thermal effects and, if the antenna is not in a dome, the wind.

As with optical telescopes, the history of millimetre/sub-millimetre antennas follows the evolution of materials technology, analysis techniques and computer control.

Antennas capable of working at 350 mm have traditionally been limited to diameters of 15 m or less. The James Clerk Maxwell Telescope (JCMT) on Mauna Kea in Hawaii is 15 m in diameter. The telescope itself is made of steel with
a series of aluminium honeycomb panels supported on a lightweight primary reflector backup structure (BUS; this is equivalent to the mirror cell on an optical telescope). At this size, it is impossible to build a steel structure that does not deform significantly under its own weight, even with very lightweight panels making up the surface. The solution is to design a homologous structure that maintains its parabolic shape as it deforms under gravity. If this can be achieved then the gravitational deformation can be corrected by a simple change in focus of the antenna (by moving the secondary mirror a few millimetres). The sub-millimetre telescopes built in the 1980s, the JCMT and the 12m Caltech Sub-millimetre Observatory, both used a truss structure design made up of bolted steel struts to make up their backing structures. Using this kind of technique, it is possible to design a homologous structure. They are, however, vulnerable to thermal gradients and wind forces and both are therefore protected by enclosures.

Next in the evolution of sub-millimetre antenna design was the utilization of carbon fibre reinforced plastic (CFRP) for the BUS. This was first used for the Swedish-ESO Sub-millimetre Telescope and Institut de Radioastronomie Millimétrique (IRAM) Interferometer telescopes and then on the Smithsonian Millimetre Array (SMA), which has antennas with backing structures made from CFRP struts. This makes the antennas stiffer, lighter and able to operate in the open air without the protection of an enclosure.

3. Astronomical instrumentation

The most revolutionary change in observational astronomy in the twentieth century was the transition from sensing with the human eye, through photographic plates to electronic detectors. Instruments based on electronic detectors provide additional challenges for precision engineering, particularly when reduction in background and detector noise requires cooling of optical systems and detectors to cryogenic temperatures, sometimes as low as 100 mK with superconducting detectors. There are four critical challenges, particularly for cryogenic instruments.

— **Differential thermal contraction** that can cause distortion or even damage to optical surfaces if not controlled.
— **Maintaining position and shape** of optical components under varying gravitational loads.
— **Minimizing thermal loads** on cooling systems—a contradictory requirement to the challenge above, as minimizing thermal loads tend towards the need for long, thin and hence flexible support structures.
— **Positioning mechanisms** such as filter wheels, grating rotators and detector positioners.

(a) **Differential thermal contraction**

It is not possible to build instruments from a single material, so there are inevitable differences in CTE between optical elements, support structures, detectors and so on. It is possible to make use of differential thermal contraction to control forces and positions within a cryogenic environment. One idea was originally proposed by Robert Hooke, to maintain the length of a clock pendulum
constant under varying temperature conditions, and thus keep better time. His pendulum was a rhombus made from one metal, with a cross truss made from a material with a different CTE. If the structure is carefully designed, an increase in temperature causes the lengths of the sides of the rhombus to increase, but the cross truss expands by a greater amount, so that the angles change and vertices of the rhombus rise to exactly compensate for the increase in length of the sides (figure 10).

A similar technique has been adopted for truss structures to support optical systems in cryogenic astronomical instruments, where there may be significant temperature differences between the optic and the structure it is supported from. In a triangular support structure, where each side of the triangle is made from the same material, as it contracts, the apex of the triangle will fall. If one of the sides of the triangle is made from a material with a different CTE, it can be designed so that the differential contraction will make the apex rise. Therefore, it is possible to arrange the lengths, angles and CTEs of the trusses so that the apex stays in exactly the same place and the supported optical system does not move. An added benefit is that the forces and hence stresses on the trusses are minimized, so that they can be of optimal shape to control thermal loads [14].

(b) Precision mechanisms at cryogenic temperatures

Another aspect of precision engineering within astronomical instruments is the need to locate and rotate optical elements. Filters need to be selected to define particular pass-bands, lenses need to be selected to change magnification, images need to be rotated to counter the field rotation caused by the telescope tracking the sky by movements in altitude–azimuth axes, and the position of detector arrays may need to be adjusted to correct for thermal or flexure effects. Often these mechanisms have to work at low temperatures, sometimes down to 4 K. Typical error budgets result in the requirements for precision of a few micrometres.
in linear position and a few microradians in tilt error; challenging to attain in a cryogenic instrument where differential contraction of structural and optical elements adds to the problem.

An example shown in figure 11 is a focus and translation unit for the Gemini Telescope Multi-object Spectrographs (GMOS) [15]. The detector array is mounted on a mechanism that allows it to be moved in three orthogonal axes. All the movements are constrained by flexures to avoid backlash and hysteresis. The $x$–$y$ axes are arranged with a system of levers, so that there is a mechanical advantage between the stepping motor drive and the movement of the detector by a factor of 10 to increase the precision of adjustment of the array. The focus direction is directly driven by a screw drive. This axis incorporates a clever mechanism, invented by John Harrison [16], the famous clockmaker, to prevent over-winding of drive springs. Here, the stopwork is used to prevent the focus mechanism from overshooting its range. Two wheels rotate at different speeds so that the lock blades rotate by a fixed number of revolutions until they come back together and form a positive, low-friction end-stop.

Another example of a precision mechanism—this time for a space-borne application—is the beam-steering mechanism built by the UK Astronomy Technology Centre for the Spectral and Photometric Imaging Receiver (SPIRE) instrument on the Herschel Space Observatory. It has to operate at 4 K, stand up to 50 g loads on launch and move to telescope image around two axes with stability of 0.03$^\circ$—all within a 4 mW power budget. A combination of flex pivots, magneto-resistive position sensors and superconducting electromagnetic actuators was used to produce a device that has worked reliably in SPIRE, operating in L2 orbit, 1.5 million km from the Earth [17] (figure 12).

(c) Precision spectroscopy

Many astrophysical processes can be probed by spectroscopy, and there has been a continual drive to increase the precision of measurement of spectral lines, produced either from emission from stellar sources or absorption in intermediate...
media such as dust and gas. One of the most challenging applications of precision spectroscopy has been for the detection of planets orbiting stars using the radial velocity technique [18]. The perturbation of position of the star caused by the planet’s rotation around it results in a small variation in its radial velocity (the velocity in the line of sight from the Earth). This can be measured by observing time variation in the Doppler shift of the spectral lines in the starlight. This technique, alongside the transit method (where planets are detected by measuring modulation of starlight caused by a planet crossing the star), has been used to discover over 500 planets at the time of writing; a notable example being a system of three planets discovered in orbit around the star Gliese 581 [19]. Spectrometers designed for radial velocity measurements need to maintain very high stability to ensure that the small variations in spectral line position measured are dominated by actual Doppler shifts, with negligible contribution from thermal and mechanical effects in the instrument itself. Using techniques such as keeping the optics at constant temperature in a vacuum vessel, and avoiding any moving parts, typical current spectrometers optimized for this application, such as the

Figure 12. The SPIRE beam-steering mirror. (Online version in colour.)
HARPS instrument on the ESO La Silla 3.6 m telescope, can achieve precision in velocity measurement of 100 cm s\(^{-1}\). Instruments for the next generation of giant telescopes are being designed to increase precision, aiming to achieve 2 cm s\(^{-1}\). To do this, it is expected that more accurate wavelength calibration based on atomic clock-controlled laser combs will be required, with frequency stability of 1 part in 10\(^{12}\) [20].

\[(d)\] Multi-object and integral field spectroscopy

Other classes of precision techniques are multi-object and integral field spectroscopy (MOS and IFS). MOS is used to measure spectra of many objects at once, such as a field of faint and distant galaxies. IFS is used to measure spectra of many points in the image of an extended source simultaneously to produce a data cube with two spatial and one wavelength dimension. A typical use for IFS would be to produce a velocity field map of a galaxy, which can be used to understand the dynamics of galaxy merger. MOS has its origins in 1980 with Roger Angel’s MEDUSA instrument, which used optical fibres glued into a plate which had holes machined in exactly the right places to align with the galaxies that were to be measured. The fibres were taken to a remote location, where they would be lined up to feed into a conventional slit spectrometer. This idea was extended in the Anglo Australian Telescope’s 2DF instrument which used a robot to place fibres connected to magnetic buttons on a steel focal plane. The latest enhancement on such ‘smart focal plane’ technology is the Echidna device used in FMOS on the Subaru telescope. Here, 400 fibres are each controlled by a piezoelectric device, and centred on a particular point in the focal plane [21].

IFS or three-dimensional spectroscopy often uses another example of ultra-precision engineering: an image slicer. The image of an object is fed onto an offset set of mirrors, which splits the object up into slices which are then realigned by a set of pupil mirrors to be fed into a long slit spectrometer. The set of spectra can then be reassembled into a three-dimensional data cube. The image slicer can be made from multiple stacked glass elements, or diamond machined from a single piece of aluminium, as in the example of the Mid InfraRed Instrument being developed for the James Webb Space Telescope. This technique, developed by Cranfield University, can produce surfaces with roughness of less than 5 nm r.m.s. (figure 13).

An instrument which combines these two techniques of MOS and IFS is now being commissioned at the UK Astronomy Technology Centre for use on ESO’s VLT. KMOS uses 24 cryogenic mechanisms to pick off individual images (figure 14). Each is fed into a slicer-based integral field unit, from where the light is reassembled to feed three spectrometers. Future instruments for extremely large telescopes (ELTs) will expand this technique to include correction for atmospheric distortion in each channel to produce even higher precision MOS and IFS—an example design being EAGLE [22].

\[(e)\] Possible future ultra-compact instruments: astrophotonics

One of the challenges of ELT instruments is size and hence cost. A future application of precision engineering based on photonics technologies could revolutionize how astronomical instruments are built. It should be possible to
build instruments at a fraction of the current size, and hopefully at lower cost, using technologies adopted from the photonics industry, including waveguide devices and photonic crystal fibres.

A conventional spectrometer uses a grating or a prism (or a combination of the two, a ‘grism’) to introduce a variable phase shift along the slit, so that light at each wavelength is focused on a different position of the detector array, resulting in a spectrum that can be recorded. An alternative is to use an array of fibres, each of slightly different length, to produce the phase shifts. Figure 15
shows the advantage of such an arrayed waveguide spectrometer compared with a conventional grating spectrometer. The fibre spectrometer can be made up to a factor of five smaller because it breaks the geometric limitations of a conventional grating spectrometer [23]. It is also possible to use photonic systems to suppress atmospheric emission, a real problem in the near-infrared owing to OH molecules in the upper atmosphere that generate a series of emission lines that reduce the sensitivity of the spectrometer. The total photon flux from OH lines can be a thousand times more than from a typical astronomical source—and it will change with time. In between the lines, the sky is very dark. It is possible to use Bragg fibre gratings to filter out individual lines using single-mode fibres. However, the telescope image of a point source (the Airy disc) contains many propagation modes, and some means must be used to split these modes so that each single mode can be fed into its own fibre OH filter and spectrometer. A device that carries out such a transformation is the ‘photonic lantern’ [24]. A precision waveguide fabrication technique using ultra-fast laser inscription is being developed [23] and holds the prospect of being able to manufacture complex three-dimensional waveguide systems in one piece of glass [25]. Such a system, if it can be realized, would lead to a revolution in infrared instrumentation.

4. The next generation of telescopes

(a) The Atacama Large Millimetre/sub-millimetre Array

The next step in the development of ground-based telescopes is arguably the most significant leap ever in astronomy—the Atacama Large Millimetre/sub-millimetre Array (ALMA) [26,27].

No telescope in operation, or under construction, has the power of ALMA for imaging the formation and evolution of stars and planets, for detecting and studying forming galaxies back to the first light in the universe, and for
analysing the chemistry and physical conditions in the cold gas in galaxies—the fundamental fuel for star formation.

The ALMA is designed to operate in the millimetre/sub-millimetre wavelength regime from around 1 cm to 300 μm. At these wavelengths, the water in the Earth’s atmosphere absorbs much of the incoming signal. The ALMA is, therefore, located at an altitude of 5000 m in the Atacama Desert in northern Chile—one of the driest places in the world, above as much of the water in the Earth’s atmosphere as possible.

Having successfully developed the La Silla Paranal Observatory in Chile, the ESO was the logical choice to be the European partner in the ALMA. The cost, approximately 1.3 billion dollars, dictated a global partnership between Europe, North America and East Asia.

In the sub-millimetre regime, it is possible to use the same coherent detection techniques as in the radio. This means that the signals from an antenna can be down-converted to lower frequency, amplified and combined with the signals from other antennas in an interferometer. Existing millimetre/sub-millimetre telescopes are either single dishes like JCMT or relatively small arrays such as the SMA or IRAM. This means that they lack both angular resolution and sensitivity compared with the state of the art of the optical or infrared. The goal of ALMA is to change that. ALMA will consist of two arrays of high-precision antennas: one made up of twelve 7 m diameter antennas operating in closely packed configurations of about 50 m in diameter, and the other of up to sixty-four 12 m antennas arranged in configurations with diameters ranging from about 150 m to 15 km. There are four more 12 m antennas to provide the ‘zero-spacing’ information, which is critical for making accurate images of extended objects.

When completed, the ALMA will give increases in both sensitivity and in angular resolution of between 10 and 100 compared with previous instruments and finally allow a detailed view of the sub-millimetre universe. This is a bigger leap than that made by the Hubble Space Telescope. Indeed, it is also larger than the step from 4 m-class optical telescopes with photomultipliers and photographic plates to 8 m-class telescopes with CCDs, in terms of combined improvements in sensitivity, frequency coverage, resolution, imaging and spectral capabilities. The capability of ALMA to make high-resolution (down to 5 milliarcsec at 900 GHz), high-fidelity images of line and continuum emission from thermal objects throughout the universe is widely recognized as the natural and necessary next step in unravelling the physics of the thermal universe.

Since the ALMA is an interferometer with the antennas separated by up to 15 km, the requirements on the project are considerably more demanding than for a single antenna of 12 m in diameter. What an interferometer does is to allow measurement of the amplitude and phase of the incoming wavefront—in the case of ALMA over a 15 km diameter area. The wavefront is sampled at each point where there is an antenna. The detected signals are all referenced to a common local oscillator signal which is distributed from a central reference to each antenna. This signal must be precise to a fraction of a wavelength over the longest baseline; this translates to a timing precision of less than 12 fs on the local oscillator signal at each antenna. The individual antennas still have the expected requirement for their surface accuracy (25 mm r.m.s.), but they also have a new requirement, that they do not introduce any significant non-repeatable path-length error as they track the astronomical source in the sky.
The Atacama Large Millimetre/submillimetre Array antennas

At the heart of ALMA are its 66 antennas. Three companies are constructing the ALMA antennas: AEM (a European consortium of Thales-Alenia Space, European Industrial Engineering and MT Mechatronics) is producing twenty-five 12m antennas, Vertex (part of the General Dynamics Corporation of the USA) is also producing twenty-five 12m antennas and MELCO (part of the Mitsubishi Electric Corporation of Japan) is producing four 12m and twelve 7m antennas.

Each of the partners, the ESO, the US National Radio Astronomy Observatory (NRAO) and the National Astronomical Observatory of Japan (NAOJ), contracted for construction of a prototype antenna that would meet specifications derived from the scientific goals of ALMA. These prototype antennas were tested at the NRAO’s Very Large Array site near Socorro in New Mexico. This prototyping phase was crucial to mitigate the risk in the project and confirm the design could meet the requirements.

The requirements on the ALMA antennas exceeded the state of the art by a considerable margin.

Environmental conditions:

— continuous day and night operation at the array operations site (AOS) at 5000m altitude in the Atacama Desert;
— strong wind conditions of 6 m s\(^{-1}\) in the day and 9 m s\(^{-1}\) at night;
— temperature extremes of \(-20^\circ C\) to \(+20^\circ C\);
— temperature gradients of \(\Delta T \leq 0.6^\circ C\) in 10 min; \(\Delta T \leq 1.8^\circ C\) in 30 min; and
— in a seismically active region.

Top-level requirements:

— 25 \(\mu\)m r.m.s. surface accuracy under all the environmental conditions;
— blind all-sky pointing of 2 arcsec r.m.s.;
— offset pointing accuracy of 0.6 arcsec over a 2° field;
— tracking of 0.6 arcsec r.m.s.;
— path-length variations less than 20 \(\mu\)m;
— fast position switching 1.5° in 1.5 s; and
— able to directly point at the Sun.

In addition, the antennas must be transportable over approximately 30 km without degrading the performance.

All of the antennas have alt-az mounts and a quadripod mounting for the subreflector (secondary mirror in optical terminology). In order to meet the stringent requirements, a significant part of the antennas is CFRP technology. The antenna BUS is a monocoque design with a CFRP skin and an aluminium honeycomb core, as are the quadripods that support the secondary mirror. In the case of the AEM antenna, the entire BUS is glued to make a single piece. It is shipped as two halves with the final gluing phase being carried out at the assembly area at the operations support facility (OSF) on site in Chile (figure 16).

In the case of the Vertex antennas, 24 CFRP segments are bolted together to make the BUS. These designs have produced very light, stiff, thermally inert structures that have been able to meet the ALMA requirements. Such designs are
only possible because it is now possible to produce complex finite-element models (FEMs) of the antennas with thousands of nodes (figure 17).

The AEM antenna also has a receiver cabin made from CFRP. All of the antenna designs have the alt-az mount structures made from steel.
The surface of each antenna is set at the OSF before the antenna is transported to the high site. This is done in two stages. The antenna vendor first sets the surface using a classical metrology technique (laser tracker or photogrammetry). This brings the surface to better than 60 mm r.m.s. The antenna is then handed over to the ALMA team, who use near-field holography at 90 GHz to set the surface to better than 25 mm r.m.s.

Figure 18 shows the surface of the first AEM antenna after setting using holography at the OSF. The residual surface error is 10.9 mm. The measured surface error must be integrated into an error budget containing terms for varying gravity deflections, thermal effects, panel ageing, etc.

Within the limits of the measurements, the ALMA antennas meet the specifications. However, the full environmental conditions can only be encountered at the AOS and so final verification of performance will be carried out at the AOS. In particular, temperatures much below freezing are not encountered at the OSF.

An extremely important aspect to be considered at the AOS is the wind. The specification calls for the antenna to remain operational up to a wind speed of 20 m s\(^{-1}\) and to fulfil all science requirements for wind up to 9.5 m s\(^{-1}\) with gusts. The AEM consortium has carried out extensive analyses in order to define the equivalent wind power spectrum to be used at the high site and to compute by computational fluid dynamics (CFD) the effect on the antenna.

*Phil. Trans. R. Soc. A* (2012)
A total of 11 load cases with the wind impinging on the antenna from different directions were computed, and the obtained field of pressure on the antenna structure and BUS has been applied to compute the expected surface displacement and the pointing effect. The various load cases have been combined and used as input to the overall antenna performance budgets. Clearly, such an approach would not have been possible a few years ago, before the advent of powerful computers and computer codes.

The design process itself is outlined in figure 19.

To meet the stringent pointing requirements, all three antenna vendors use active metrology systems. These systems measure the real-time deformation of the antenna structures owing to thermal loading and wind and feed this back to the antenna pointing control system. The AEM antennas have 86 temperature sensors distributed inside the steel structure of the mount; this allows the deformation of the structure to be modelled and corrected.

For the axis control, the AEM consortium developed, via their supplier Microgate, a new high-speed tilt meter (patented) to allow their metrology system to correct for wind buffeting as well as mean wind displacement. This tilt meter
has performance similar to or exceeding that of available devices on the market in static condition, but additionally can recover from an antenna slew in fractions of a second, allowing measuring of sub-arcsecond deflections in the antenna, while the antenna is rapidly moving between sources on the sky.

Meeting the pointing requirements is possibly the most challenging of all the ALMA antenna requirements. The complete antenna weighs a little over 100 tonnes, and must be able to fast switch $1.5^\circ$ in 1.5 s and then immediately settle and track with 0.6 arcsec accuracy. It must also be able to offset point to within 0.6 arcsec r.m.s. and blind point over the entire sky with an accuracy of 2 arcsec r.m.s. The AEM antennas meet these demanding requirements by (i) minimizing the moment of inertia of the antenna by making the receiver cabin out of CFRP rather than steel and (ii) using direct drive motors. Direct drive systems are common on optical telescopes and comfortably meet the tracking requirements. Making them rugged enough to work in the open air was the major challenge. By comparison, Vertex pushed the gear and pinion drive technology used on classical radio telescopes to its very limit, using very stiff gearboxes and high-quality motors with very little cogging. Both solutions have been shown to work.

The pointing of the antennas was verified at the OSF using an optical pointing telescope that looks out through a small hole in the primary reflector of the antenna.

Figure 20 shows the residual errors from the all-sky pointing tests of the first AEM antenna. The r.m.s. error is 1.0 arcsec, a value routinely achieved by this antenna, and comfortably within the requirement. Figure 21 shows the servo errors during a fast switch on both axes corresponding to $2^\circ$ on the sky. Again it can be seen that the errors are comfortably within the 1.5 arcsec requirements after 1.5 s of time. No trace of overshoot is visible.

Figure 22 shows the all-sky pointing tests from the Vertex antennas. In this case, the antenna had been left facing into the Sun for several hours around sunset, thereby creating a strong thermal gradient in the antenna. Then as soon as the Sun set, an all-sky pointing run was carried out. The metrology system was then alternately turned on and off for each star. In this way, two datasets were obtained simultaneously, one with metrology active and one with it off. The lower part of the figure is with metrology on and the all-sky r.m.s. is 1.01 arcsec. Without the metrology, huge residuals can be seen which would easily take the antenna out of specification if they were not corrected.
The most difficult pointing specification to verify at the OSF is the offset pointing. Here, the requirement is an offset pointing accuracy of 0.6 arcsec over a 2° field. However, the measurement is being made with an optical pointing telescope that has 0.9 arcsec pixels and in the presence of optical seeing (typically 0.3 arcsec at night). Then the data, which are measured at the OSF (with quite a low wind speed), have to be extrapolated to predict how the antenna radio pointing will perform at worst-case wind speeds at the AOS. Within the measurement errors, which are about 0.2 arcsec, the offset pointing of the ALMA antennas meets the requirements. This will also be verified at the AOS interferometrically.

(ii) Correcting for the effects of the atmosphere

The Earth’s atmosphere not only absorbs the incoming signals, it has a variable refractive index and so distorts the incoming wavefront. This produces ‘seeing’ which distorts the images ALMA sees by producing phase errors induced by variations in the atmospheric path-delay—washing out the final images. This anomalous refraction is variable and can result from water vapour and from variations in the density of the dry component of the atmosphere.

Two strategies have been adopted to correct for this. The first is to directly measure the amount of water vapour in the line of sight of each antenna. This is done by measuring the emission from the atmosphere in the 183.31 GHz water line. Each 12 m antenna is equipped with a dedicated water-vapour radiometer for this. The measured emission is fed into a model to predict the phase correction needed once per second. This method, however, does not measure the dry
Figure 22. All-sky pointing tests on the Vertex antennas showing the effects of the metrology correction. (Online version in colour.)
component of the atmosphere. This is done by the second method—fast switching. Here, the entire array is switched to a nearby calibration point source at rates varying from once every 10 s to once every 5 min. Since a point source has a known structure, it can be used to zero out any phase errors before fast switching back to the astronomical target and continuing the observation.

(iii) **Current status of Atacama Large Millimetre/submillimetre Array**

At present, design and development of the ALMA have been completed successfully, and the project is well into series production of the myriad of components, subassemblies and subsystems that make up the whole system. Figure 23 shows the antenna integration activity at the OSF. This photograph is taken from the top of the 50 m high holography tower and shows six AEM antennas in various stages of assembly and testing in the foreground.

Once the ALMA had 16 antennas operating at the AOS (the first eight are shown in figure 24), it was significantly more powerful than any previously existing facility. At this point, early science operations started. Antennas are currently being added to the array until the full complement of 66 antennas is achieved.

(b) **The European Extremely Large Telescope**

(i) **Motivation**

While astronomy has expanded out into new wavelength bands such as the sub-millimetre, many important discoveries are still made in the visible and near-infrared regimes, where stars predominantly emit their light. For example, the first exoplanets (planets orbiting other stars) have been detected, and the current generation of 8–10 m class telescopes has even allowed us to take the first pictures of a few of these objects. Another example is the detection of previously completely unsuspected dark energy, believed today to dominate and to drive the expansion of our universe. Our knowledge in astronomy continues to progress at an incredible pace, answering many questions, but also raising exciting new ones. The E-ELT will address these new fields; 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.
The 8 m class of meniscus mirror telescopes represent a natural limit for single mirrors. Casting mirrors larger than this is very problematic due to the problems of distortion and inclusions during cooling. A very successful alternative to thin ‘meniscus’ active mirrors was developed by Roger Angel at the Steward Observatory, from an idea attributed to Isaac Newton [28]. Borosilicate glass blocks are contained in a mould that is spun inside a furnace, resulting in a parabolic shape owing to centrifugal forces. This produces mirrors with excellent thermal and mechanical properties and has been used to make the world’s biggest monolithic mirror, at 8.4 m diameter, for the Large Binocular Telescope (LBT). The LBT is built from two of these mirrors mounted in a common tilting and
rotating (alt-az) structure. However, even that technique is not practical for larger telescopes, partly because of the difficulty of transporting large mirrors to high mountain sites.

The breakthrough technology that enables consideration of building even bigger telescopes—the ‘ELTs’—came from Jerry Nelson [29]. He developed the idea of using segmented mirrors to make the 10 m diameter WM Keck telescopes, each with 36 hexagonal segments very carefully aligned to construct what is close to a single mirror surface. This technique was first employed by Guido Horn D’Arturo [30] in Bologna between 1935 and 1953. He assembled 61 hexagonal mirrors to form a 1.8 m fixed zenith-pointing telescope. However, each mirror was aligned by hand, probably providing the explanation as to why nobody copied his idea until precision edge position measurement and computer-controlled actuation became available. Jerry Nelson’s team solved these problems, and opened up the prospect of building ever-larger telescopes, probably limited by the availability of money, not technology.

Following on the success of the VLT, the ESO began a study in the late 1990s and early 2000s to explore the limits of telescope design. This work was centred on ELTs with diameters of 100 m. That early work culminated in a body of knowledge that allowed a project to be defined that was deemed to be a reasonable compromise between scientific ambition and cost and schedule risk. From the studies already carried out, it was clear that a 40 m class telescope would cost of the order of a billion euros. In the second half of 2006, a project office was established at the ESO and a baseline design was established for a E-ELT. This baseline design formed the reference documentation submitted to the ESO Council as a proposal to move to a detailed design phase, known as phase B, the results of which are now available.

(ii) Design philosophy

In phase B, the E-ELT project has established the top-level requirements from the science requirements and launched a series of industrial studies. For each subsystem, a preliminary design was carried out by industry. These designs define the major components of the system and demonstrate that performance can be met through analysis. At this point, mass and volume budgets were established, interfaces to other subsystems established and plausible cost estimates from industry evaluated. The preliminary design output included a thorough revision of the requirements and the technical specification for the next stage of the design. The next stage used the front end engineering design (FEED) process. This is a detailed design stage in which FEED studies are undertaken by industry based on the requirements output by the earlier design stages. The FEED detailed design output is sufficient to be able to tender for construction contracts. To both mitigate risk and generate competition, this work involved generating competing designs in industry. Industry was also engaged to provide an independent review of the work.

(iii) Design

The E-ELT will be located on Cerro Armazones (figure 25) which adjoins the existing VLT site at Cerro Paranal.
The E-ELT is an adaptive optics telescope, delivering images with some level of correction for the atmosphere at all times. It has been conceived and will be operated as an adaptive telescope and not a telescope with adaptive optics. The elliptical primary mirror has a diameter of approximately 39m and is made up of 798 segments. With such a large segmented mirror, it is necessary to constantly control the shape of the primary and to constantly correct any errors in the wavefront by adjusting the optics. It is therefore natural to incorporate the correction of distortions of the incoming wavefront owing to both the telescope and the atmosphere.

The optical design of the telescope is a departure from the classical designs employed in 8m class telescopes. It is a three-mirror anastigmat together with two folding flats that are used to extract the beam to a Nasmyth focus (figure 26). Such a design is nearly diffraction limited over the entire 10 arcmin field of view. It also has some features that are highly desirable for an ELT. The flat quaternary mirror (M4), which is a natural consequence of the optical design, is also a high-order deformable mirror with some 6000 actuators. This makes correction for the atmosphere an inherent part of the telescope. Another advantage is that the folding flat fifth mirror (M5) can be a fast tip-tilt mirror. This mirror corrects linear image motion errors owing to the atmosphere and owing to wind buffeting of the telescope. Such a function is done using a tip-tilt secondary mirror on smaller telescopes, but on an ELT, the secondary mirror is too large to be able to do this with current technology.

The optics are mounted on an alt-az 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 2800 tonnes. In the central obstruction of the primary a 15m tall tower supports the quaternary and M5 mirrors (figure 27).

To correct the incoming wavefront and control the mirrors using both active and adaptive optics, it is necessary to observe the so-called ‘guide stars’. Since a star is known to be a point source of light, the incoming wavefront should be a plane wave—any aberrations measured therefore must be due to either the atmosphere or the telescope and are corrected in closed loop by the various moveable and deformable mirrors. In order to do this however, it is necessary to be able to find sufficient numbers of guide stars near the astronomical object of interest. Simply using natural guide stars does not provide anywhere near full sky coverage for the E-ELT and so a constellation of laser guide stars will be launched upwards from the telescope and will surround the target. The laser guide stars come from shining yellow 589nm lasers up into the high atmosphere where they excite sodium atoms which then reradiate providing an artificial star. Prototype lasers with power outputs of 20 W have been developed to do this and will shortly be deployed on the VLT.

(iv) Analysis tools

It would not be possible to build an instrument as complex as the E-ELT without sophisticated analysis tools to model the behaviour at system level. Three sets of toolkits are used to predict the performance of the telescope and its adaptive optics systems. The diffraction-limited performance simulations are made using an adaptive optics toolkit based on sophisticated models of
the atmosphere and the adaptive optics control system. The telescope main structure and control simulations provide static and dynamic analyses of the entire telescope structure and the optical systems, to understand the design and evaluate the effects of perturbations such as gravity, earthquake, thermal and wind. Finally, an optical model follows the propagation of the light beam through the telescope taking into account the translations and displacements of the mirror units, available from the time simulations of the control/mechanical models. In this way, the dynamic performance of the telescope can be characterized in terms of wavefront aberrations and compared with the error budget to ensure the performance requirements are met.

(v) The primary mirror

The E-ELT primary mirror comprises 798 low-CTE glass segments. As with the Keck telescope, a hexagonal geometry has been selected. The segments are 1.45 m from corner to corner and 50 mm thick at the centre. The thickness is selected such that the distortion under gravity and other loads is manageable, while at the same time maximizing the number of segments extracted from each boule of glass. The segments are supported axially on identical 27-point...
whiffle trees. The segment and supporting structure is moved in piston and tip-tilt using three position actuators. The whiffle tree loads can be adjusted using one or more of 12 warping harnesses to correct for low-order aberrations on the individual segments. Inductive edge-sensors are used to provide direct feedback to the position actuators and for global control of the mirror shape.

The polishing specification of the segment, including the integration on the supporting structure, requires that a segment does not exceed 100 nm r.m.s. maximum wavefront error and 50 nm r.m.s. wavefront averaging over all the segments. After correction of 85 per cent of focus, astigmatism and 85 per cent of trefoil (a higher order aberration) by the warping harnesses, the maximum error will reduce to being less than 30 nm r.m.s. wavefront and 15 nm r.m.s. wavefront on average.

During phase B, an extensive campaign of prototyping has been carried out with M1 segments, whiffle trees, position actuators and edge-sensors all being demonstrated to meet the E-ELT needs.

(vi) Next steps

At present, the detailed design of the E-ELT has recently completed a final iteration to address risk items and to finalize the cost estimate with a view to formal approval to move into construction in 2012 (figure 28).
5. Conclusion: precision engineering in astronomy

The development of astronomical telescopes and instruments over the last 400 years has provided many challenges that have been solved by the application of precision engineering. For more detail, especially on the development of metrology techniques, see Shore et al. [31]. It seems highly appropriate to this meeting that was approved by the Royal Society’s Hooke Committee that many owe their resolution to the ideas of Robert Hooke. It is also true that the engineering solutions that have been driven by the high demands of astronomy have had major impacts in other fields—an important future possibility being the ultra-precision optical mirrors being developed for the ELTs that could end up contributing to laser-confinement fusion energy.


References


*Phil. Trans. R. Soc. A* (2012)
8 Newton, I. 1672 An extract of a letter, received very lately, (March 19th) from the inventor of this new telescope, from Cambridge. Phil. Trans. R. Soc. A 81, 4009–4010.