The European Extremely Large Telescope (E-ELT)

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The ESO Council has authorised the E-ELT project to move to Phase B and approved the budget for the further design of the telescope and its instrumentation. In this article we present the activities and design concepts considered in the past year leading up to the decision of Council.

In the March 2006 Messenger the path towards a basic reference design for a European Extremely Large telescope was presented. The plan involved extensive community consultation through five working groups, established by the Director General of ESO, on the topics of science, site, adaptive optics, instrumentation and telescope. The conclusions of the ELT Scientific and Engineering (ESE) Working Group panels were combined into a toolbox which was used as a guide by the ESO ELT Project Office towards determining a Basic Reference Design to be presented to the community and the committees of ESO. The basic premise underlying these activities is the strategic resolution of the ESO Council that requires that the organisation develop a facility that will address the exciting science awaiting us in the coming decade and will be competitive in timescale and performance with similar facilities planned elsewhere.

The toolbox generated very specific goals to be addressed in the design phase. The telescope to be built should have a primary mirror of order 40 m in diameter (42 m was thought to be a good compromise between ambition and timeliness), should not be based on spherical mirrors, should have adaptive optics built into it and deliver a science field of view of at least five arcminutes diameter with a strong preference for larger fields. Furthermore the telescope was to provide multiple stable observing platforms while maintaining a focal ratio that would be favourable to instrumentation.

Additional inputs to the design of the telescope came from the conclusions of the OWL review held in November 2005. While that review concluded that the ELT project could advance into the next phase, the panel recommended that certain high-risk items be avoided in the next iteration of the design. Double segmentation (on OWL the primary and secondary were both segmented) and the high complexity of the adaptive mirror (in OWL the sixth mirror combined field stabilisation and adaptive corrections in a single unit) were considered risks that would delay or jeopardise the project. The fast focal ratio of the telescope (f/6) and the absence of gravity invariant focal stations were also on the hit list of things to be avoided in the redesign.

The ELT Project Office at ESO worked during 2006 to determine whether a telescope that can meet these requirements can be designed and constructed within reasonable timescales and for plausible costs. Some work has been performed in-house at ESO, while some activities have been contracted to industry. In parallel to these pre-design activities, many cost estimates have been received from industrial suppliers.

The optical design

In the process of evaluating the options for the European ELT, two candidate designs were recommended by the ESE working groups to be considered in more detail. A classical Gregorian design and a novel five-mirror design were submitted to detailed trade-off analyses (see Figure 1). The design process has been followed by the ESE subcommittee of the STC and within that framework, meetings with the telescope, science and instrumentation working groups have been held.

Both telescopes are based on 42-m diameter aspheric primary mirrors, on the elliptical side of the parabola, and to be assembled using more than 900 hexagonal segments (petals are also an option but not in the current baseline), each approximately 1.45 m peak-to-peak in size. The Gregorian design has a 4.8-m concave secondary and can either exploit the beam at a deep Cassegrain location or, using a tertiary 5-m flat, redirect the beam to a Nasmyth focus. In the five-mirror design, an active convex 6-m secondary mirror is followed by a concave, mildly aspheric, tertiary mirror located within the central obstruction of the primary. Two flat mirrors relay the beam to the Nasmyth foci of the telescope. Both optical designs deliver a 10 arcminute diameter, f/15 beam at the Nasmyth focus. In the Gregorian the field is limited by the size of the tertiary, while in the five-mirror design the size of the hole in the quaternary mirror defines the field and the central obstruction.

Before we delve into the details of the design and the trade-offs, the primary mirror

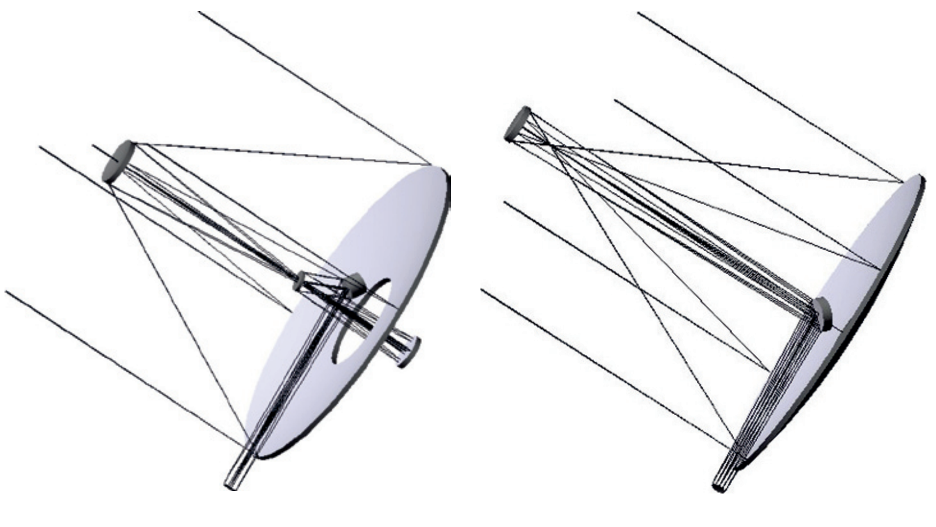

Figure 1: The two optical designs considered during the Basic Reference Design development: five-mirror (left) and Gregorian (right).

of the telescope deserves some attention. The primary of the E-ELT will need to be phased and, to this purpose, we have been working within the FP6 ELT Design Study programme, and within the Project Office, to develop both a phasing methodology and the requisite sensors. The active phasing experiment will test different phasing sensors on a small segmented mirror. It is to be mounted at the visitor focus of the VLT and in this way we expect that the telescope's ability to produce (as well as cancel) aberrations on demand can be used to optimise the process of phasing. Sophisticated sensors and actuators are under development in industry as part of the FP6 programme. At ESO we recognise that we have almost no experience in matters associated with segmented mirrors. The entry of Spain into ESO will bring this expertise into the organisation and, with a number of technical nights available to ESO on the GTC, we hope to greatly expand our knowledge base.

To build adaptive optics into the telescope, as recommended by the ESE working groups, a convenient location for an adaptive mirror is required. In the Gregorian design, the deformable mirror is the secondary that is naturally conjugated to the ground layer. That deformable mirror will also need to look after the tip-tilt component of the wavefront error. In the five-mirror design the deformable mirror is the quaternary, also conjugated to the ground layer, while the fifth mirror in the optical train provides for tip-tilt compensation.

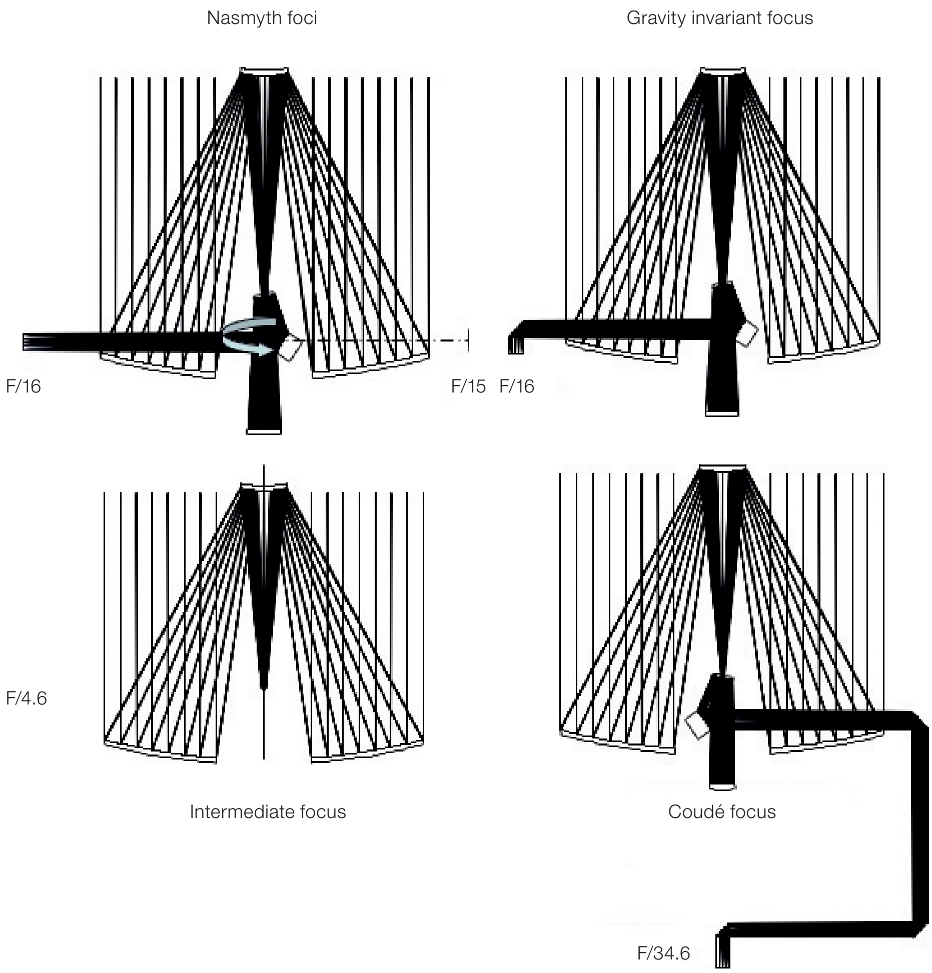

Figure 2: Different foci can be supported by changing the focal length of the telescope. In the five-mirror design, shown here, this is achieved by moving the tertiary mirror along the telescope axis. An intermediate, two-reflection focus can also be provided.

The five-mirror design

The simplicity and elegance of the Gregorian design would make it a front-runner. The minimum number of mirrors is necessary to relay the beam and it provides a prime focus, particularly useful when wishing to calibrate the adaptive mirror. Furthermore concave mirrors that are easier to polish. So why study an alternative? The issue at hand is that large telescopes are very difficult to build and a natural question is: "Is there a better solution to the traditional telescope?"

What is so challenging about large telescopes? It is hard to find any single area where the increased size of the telescope makes things easier. The simplification made by segmenting the primary mirror is easily compensated by our wish to have the primary as large as possible.

Both the Gregorian and the five-mirror designs provide excellent image quality across the field of view. The Gregorian has field aberrations increasing with distance from the centre of the field of view, but their contribution to the image quality will be limited to well below any reasonable expectation for the natural seeing. With three powered mirrors, the five-mirror design delivers nearly perfect image quality across the entire field of view.

Furthermore, big telescopes have awkward focal planes. The linear dimensions of the ten-arcminute field of view of the E-ELT are similar to those of the VLT at Nasmyth. However, only one ninth of the area of the sky is imaged. The plate scale and its matching to any detector system or slit are serious challenges for instrumentation, while at the same time a faster focal ratio would severely limit the working volume for the construction of instruments. Another problem is how to provide for a relatively flat focal plane for the instruments. Classical designs of telescopes, such as the Ritchey-Chrétien or the Gregorian, have significant field curvature (for an E-ELT with the Gregorian solution, the radius of curvature at the focal plane is of the order of 4 m) and rely upon field flattening lenses or mirrors in the instruments to generate the field flatness. This solution is economical in optical surfaces, as often some optics would be required in any case for the window of a cryostat and giving it the right properties to compensate for field curvature does not overcomplicate the instrument. This, however, places very strict alignment requirements on the instrument relative to the telescope.

For the Gregorian design a further complication arises as the direction towards the centre of the field curvature is inverted, relative to the direction of the chief ray from the telescope, at any particular location in the field. While as mentioned above, field flatteners are common-place, for the field of view of an E-ELT they need to be segmented and off-axis. Doing without this complication certainly helps.

With three powered mirrors, the five-mirror design delivers a focal plane that is largely un-aberrated at all field locations and the chief ray and the axis of the very limited field curvature (radius of 36 m and convex as seen from the instrument) are parallel. To all intents and purposes it does not matter where in the focal plane you mount your instrument. The focal plane properties are uniformly excellent in the five-mirror design.

The mechanical structure

The next stage in the design process is to create a mechanical concept that meets: the needs of the optics to be kept in place; the needs of the instrumentation for accessible foci; and the needs of maintenance to be able to reach the optics. Of course all of this has to be done for the lowest possible cost while providing the maximum possible performance.

The basic mechanical design of the E-ELT baseline is an altitude over azimuth mount, with a grid-like structure made of multiple identical components. The result looks boxy but is light and designed to be easy to manufacture and transport. There are very few large elements in the telescope. The azimuth platform rests on four concentric hydrostatic tracks providing axial support to the telescope, while the radial direction is constrained using a central bearing. The elevation structure is supported by four cradles that transfer the loads directly through to the same azimuth bearings. Here again hydrostatic bearings are envisaged. The cradles of the altitude extend above the level of the primary mirror in order to provide sufficient support to the telescope to reach the horizon pointing location. Direct drive motors (as are used in the VLT) are foreseen to move the telescope. The mechanical structure is very similar for both the Gregorian and five-mirror designs. The structure supporting the secondary mirror is a three pier system located at 120 degree intervals around the primary mirror. At the top of the three towers, the spider of the telescope supports the secondary unit while at the same time minimising the obstruction of the beam. The current design avoids the use of 'ropes' that would provide additional stiffness but cause extra diffraction patterns in the PSF. This is regarded as an advantage by the extrasolar planet-searching community who hope to go beyond searching and into studying the planets themselves. The project hopes to be able to maintain such a configuration in the final telescope.

The telescope is mounted on a central concrete pier that ensures a minimum clearance of 10 m above the ground is maintained throughout the operational range of down to 30 degrees above the horizon. An enclosure/dome is foreseen to protect the telescope from the elements. The enclosure studies are ongoing through the FP6 ELT studies and activities within the ELT Project Office. Various options exist for an enclosure for the telescope. As is described below, the size and design of the enclosure becomes a critical issue when considering the effects of the wind on the telescope structure.

Controlling the telescope

One of the biggest challenges of a large telescope is to provide for the stability of the images. Large telescopes tend to shake in the wind. As a result the images will also shake and possibly be distorted as the optics may become ever

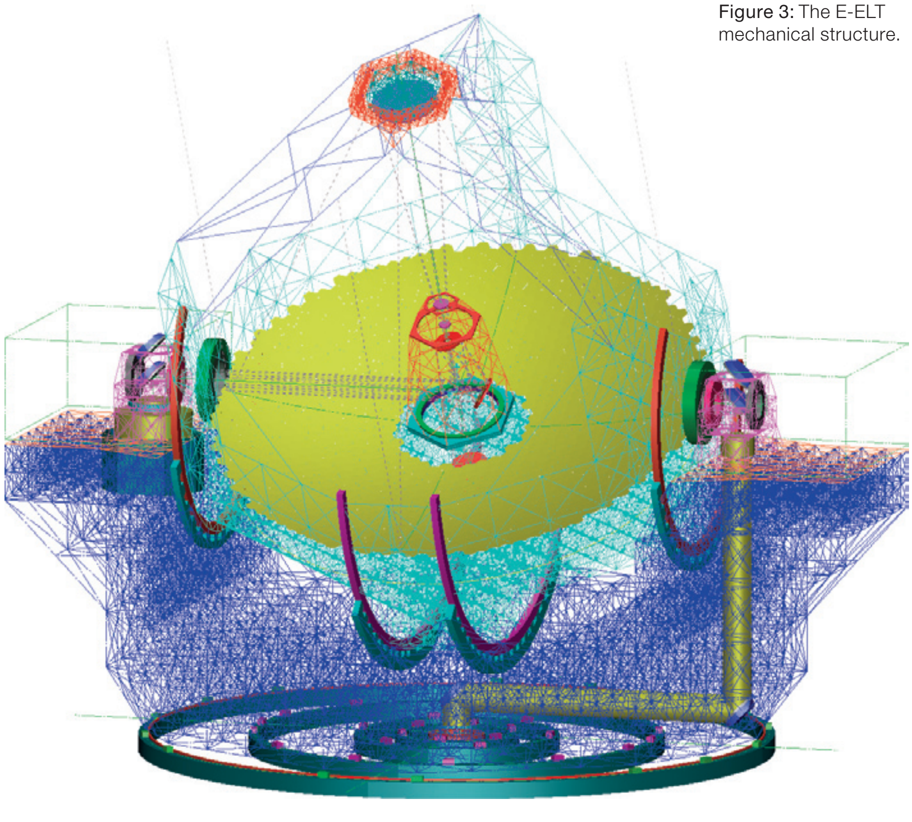

Figure 3: The E-ELT mechanical structure.

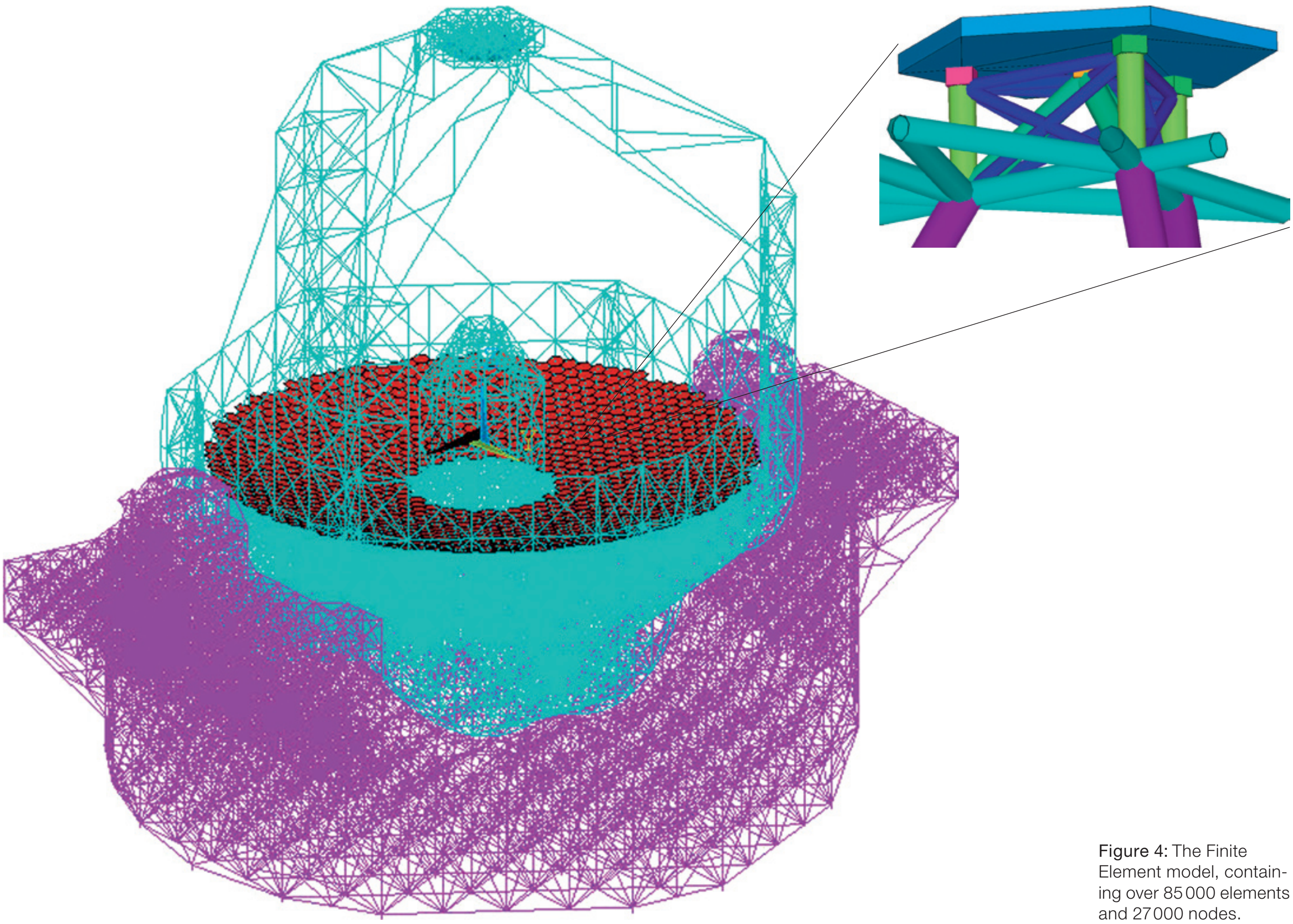

Figure 4: The Finite Element model, containing over 85 000 elements and 27 000 nodes.

so slightly misaligned. This is not a new problem and in fact the tradition of enormous domes protecting the telescopes has, to a large extent, been the first defence against the wind. Large domes however had a negative effect, detected in many of the 4-m-class telescopes, namely dome seeing. In the evolution of telescope-system design a critical step was the open structure of the MMT – a solution later adopted also for the ESO NTT. Exposing those telescopes to the wind provided, on the one hand, clean air, but required that the mechanical structures were stiff enough to withstand the effects of the wind. With 4-m-class telescopes and alt-azimuth designs, it has been possible to achieve eigenfrequencies of well above 10 Hz (an order of magnitude higher than the equatorial mounts of the 1970's).

For the 8–10-m class telescopes, the mechanical structures were even larger and the eigenfrequencies lower. For example the VLT Unit telescopes start at a very respectable 8 Hz. To combat the effects of the wind on the 8-m telescopes, rather than employing enormous domes another choice was available, viz. field stabilisation, the rapid correction of the effects of wind shake with a fast steerable mirror, located somewhere conveniently close to the pupil of the telescope. The deployment of such mirrors in UTs, and also in the Gemini 8-m telescopes, has permitted very compact enclosures and excellent ventilation. As a side benefit, exceptional tracking performance is delivered by the telescope systems at the focal plane. The telescope may well be all over the place (figuratively speaking) but the focal plane stays put.

As we move to the large telescopes of the future the challenge of the wind shake returns. Before we decide how to address this issue we need first to establish its scale. To do this, a fairly sophisticated finite element model of the telescope is required, with of course the subsequent analysis, comprising models of the servo systems, the impact of mechanical deflections on the optical performance, etc. A number of iterations around this loop are needed before something plausible can be extracted for a design/performance trade-off.

For the E-ELT we have iterated our design against the requirements using a Finite Element model with over 85 000 elements and 27 000 nodes that was constructed for both the Gregorian and the five-mirror optical designs. The first eigenfrequencies of the mechanical design are around

2.5 Hz, almost irrespective of optical design. These are decently high for a 5 500-ton structure that carries a telescope 'tube' that is just under and just over 40 m long for the five-mirror and Gregorian solutions respectively. It is interesting to note that the five-mirror design makes for a telescope that is wider than it is long. The size of the dome will be dictated by the Nasmyth platforms, rather than the telescope 'tube'. The static analysis of the structure shows us that we can build it without resorting to exotic materials and only in few locations may need to employ anything but the most normal of steel. The analysis also shows that the structural design is in principle compatible with sites with high earthquake risks, although again certain locations may need reinforcement. Of some concern are the large accelerations that the secondary units of both designs are subjected to in case of earthquake.

Irrespective of the optical design, one challenge for the telescope will be to maintain collimation. The static deflections of the secondary mirror relative to the primary are large and cannot easily be accommodated within a classical NTT-like system of re-alignment during operations. Maintaining a decent wavefront from the telescope will not be easy.

The impact of the wind

Having a structure that can support the optics, we now discuss the impact of the wind. Various wind loading assumptions have been made. Open air has been used as the benchmark. A VLT-like box-style, tightly fitting, enclosure provides limited protection from the wind and even in some cases shifts some the wind power to higher frequencies, something that is not favourable. A TMT-like calotte design was also considered as it provides for a much better damping of the wind, partly by restricting the opening to the wind and partly by having a dome somewhat larger than absolutely required by the telescope.

In either case, the analysis made for the 42-m telescope clearly indicates that making the telescope deliver good images in a passive mode and under reasonable wind loads is going to be very difficult without a field stabilisation stage. In short, the tip-tilt component of the wavefront, attributable to the telescope under relatively strong winds, is expected to be on the order of 0.8 arcseconds rms, irrespective of optical design. A smaller telescope with a bigger dome could reduce this to below 0.2 arcseconds and possibly even lower. However, we should recall that, thanks to the recommendation that the telescope be adaptive, we already have a tip-tilt capable mirror in our optical train.

The issue at hand is how to address a 0.8-arcsecond tip-tilt component with a large (2.5- or 4.8-m mirror). The edge of the mirror will be moving by a number of 100's of microns, if it is to provide for the required tip (or tilt), and it will need to do so at frequencies of some tens of Hz.

The Project Office contracted design studies to a number of industrial firms to develop a solution to this problem. The studies were embedded within a more complete package of providing conceptual designs for the entire adaptive optics system, for either or both of the Gregorian and five-mirror optical designs. Two industrial firms provided solutions for the 4.8-m Gregorian mirror. The tip-tilt capability of the mirror is to be achieved by segmenting the support structure of the mirror (and the front face) and providing a tip-tilt capability in each of the segments. Synchronously tip-tilting as many as 18 segments (in phase) provides for a global tip-tilt. The number of segments and details of the technology differ depending on the supplier, but the underlying principle, of a thin face sheet of glass being supported by actuators mounted on a support structure, is the same[1] for both designs.

In the case of the five-mirror design three options for the field stabilisation stage were provided in our consultation with industry. As in the five-mirror design, since the fifth mirror is 'only' 2.7-m in size segmentation has not been seen as necessary and, although some novel ideas are being considered, we believe that this is a tractable problem.

An adaptive telescope

An adaptive telescope is the natural evolution of the active telescope that ESO pioneered with the NTT. There are many reasons why active optics was a great advance in telescope design and it is worth elaborating somewhat on them here. In order to deliver good images, a telescope not only has to be at a good site, but also has to be a good telescope. More than just having the right optics, the optics has to be properly aligned and kept that way. In the past century, colossal advances were made in optical materials that allowed the mirrors to maintain their polished surfaces to the correct prescription. With the use of the Serrurier truss, classical telescopes maintained their collimation to the accuracy needed for arcsecond and even sub-arcsecond images. Much, if not all of this, was pioneered on the 200-inch at Palomar. However, it is worth noting that a number of the 4-m telescopes were found to have the wrong prescription polished into some of their mirrors or not to be correctly aligned. Exceptional images from the CFHT and the NTT changed the expectations of astronomers.

A number of innovations were tested at the NTT, but we shall concentrate here on the active optics. The collimation of the telescope (rolling the M2 about the coma-free point during observations to align it with M1) was critical for the performance of the telescope. The active support of the primary to compensate for gravitational deformation was not absolutely necessary in the NTT, as the primary was conservatively made thick enough to be able to operate without it. However, it worked remarkably well and the success of the active deformation ensured that we could make thin meniscus mirrors for the VLT within reasonable schedules and costs. The unit telescopes of the VLT run in closed-loop active optics at all times and have done so since the first star was detected in April of 1998. Millions of corrections have now been made and this operational mode has been critical to the high efficiency of

[1] Each segment of the large deformable mirror is similar in size and complexity to the current generation of large deformable mirrors, such as those deployed at the MMT, in the process of deployment at the LBT and in manufacturing for the VLT and Magellan telescopes.

the observatory, as no time is ever wasted focusing or checking the telescope performance.

This rather lengthy aside leads us to the reasons adaptive optics should be part of the telescope of the future. With exacting requirements on image quality, an E-ELT will need to keep objects with good PSFs in very precise positions on the focal plane. In addition to the instruments requiring excellent images, the wavefront sensors also benefit from this good image quality. The distortions of the wavefront, whether from the telescope or the atmosphere, need to be taken into account. Active optics can handle slow variations, and for the VLT the residual is pure tip-tilt which can in that case be taken out at the secondary. For an E-ELT the residual is more than just tip-tilt and therefore other low-order aberrations will need to be corrected. If you fix them in the telescope, you need not do it in the instruments. An alternative design choice would be to fix the telescope aberrations in each instrument. For the E-ELT, we believe that we will need this capability anyway for each instrument and therefore we do better to fix this problem once and for all. The penalty of doing it once is that you do it for the entire field, rather than the special needs of any given instrument.

As telescopes become increasingly large, it is not immediately obvious how one goes about building instruments for them without breaking the budget. Long focal lengths are needed to provide sufficiently large back focal distances and reasonably powered mirrors in the telescopes. However, slow optics also imply pixel scales that are less favourable for seeing-limited observations. Big telescopes do not allow for big pixels in the cameras. Small pixels not only mean that many more of them will be needed to cover some patch of sky, but also that the sensitivity of the system depends greatly on the image quality of the telescope. The bottom line is that if the telescope is adaptive then making the instruments for it is easier. Critics are likely to argue that the global problem may be harder to solve. We hope to address this during the design phase of the telescope.

The adaptive mirrors

The adaptive mirror will of course correct for the atmospheric wavefront errors. This challenge can be relatively straightforwardly (an unfair choice of words given the enormous task that underlies this statement) translated into a requirement of spatial and temporal flexibility of the glass. The spatial requirement is typically expressed with two numbers: the pitch of the actuators (or inter-actuator spacing) and their stroke. The temporal requirement is exactly that: namely, how fast can an actuator get to the required position and with what accuracy.

When the actuator spacing, as projected on the primary of the telescope, is small, then the actuators map better on to the atmospheric turbulence scale-length and the resulting correction is better. The stroke has to be sufficient to correct the low-order aberrations and the temporal issue is relatively simple: faster is better. Stroke, pitch and actuator rise times are all technological issues. As mentioned above, the Project Office contracted industrial partners to evaluate the requirements and the specifications for the adaptive optics systems of the two designs for the E-ELT.

Over the past years and in the context of both the past ELT studies at ESO and the FP6 framework, very sophisticated simulations have been used to derive performance requirements for adaptive mirrors to be used in ELTs. Within the E-ELT Project Office we are using this simulation environment to validate the various design options and make choices.

During the selection of the baseline reference design, we investigated the adaptive capabilities of the two designs. This is very much technology-driven. For example, starting from a 30-mm actuator pitch on the Gregorian 4.8-m mirror we would have over 20 000 actuators projected on to the primary, the equivalent of a 20-cm pitch there. The same 30-mm actuator pitch on the 2.5-m quaternary mirror of the five-mirror design only provides 5 000 actuators and a 50-cm pitch on the primary. It is clear that the Gregorian adaptive mirror would deliver better AO performance thanks to the higher number of actuators.

Artificial guide stars

Another part of the adaptive optics puzzle are the laser guide stars to be used to provide the high number of photons required to make fast corrections. Natural guide stars will also be needed to correct for low-order aberrations. Telescopes are focused at infinity, while laser guide stars are images at the sodium layer at a distance of 90 to 160 km from the telescope. The laser guide star images at the telescope focal plane appear significantly aberrated, defocus being the obvious aberration. The in-focus images of the laser guide stars appear as much as 5 m behind (i.e. away from) the telescope focal plane. The extent of the defocus is such that the footprint of the lasers, at the location of the natural guide star adapter, is of the order of a fifth of the total field of view.

While in theory a dichroic could separate off the sodium light and send it in a direction perpendicular to that of the light from the telescope, this solution cannot possibly cover the entire linear field of view of the telescope at the Nasmyth focus, unless the dichroic were also to be segmented. Additionally, going through dichroics introduced non-common path errors for the adaptive optics to handle.

To solve this problem we propose to have a separate adapter for the laser guide stars that will receive the beam from close to the focal plane of the telescope by reflection. The differential focus, as the distance to the sodium layer changes, will be accommodated using relatively simple zoom optics within the laser guide probe systems.

Defocus unfortunately is not the only aberration to be handled. Aberrations in the laser guide stars can of course be handled if they are static. However, they change with the changing distance to the sodium layer. The five-mirror design in this respect has a big advantage over the more classical designs. With three powered mirrors the residual aberrations of the laser guide stars are of the order of 0.3 waves, while for the Gregorian the equivalent is of the order of 4 waves.

Another issue for E-ELTs is the spot elongation of the laser guide stars when

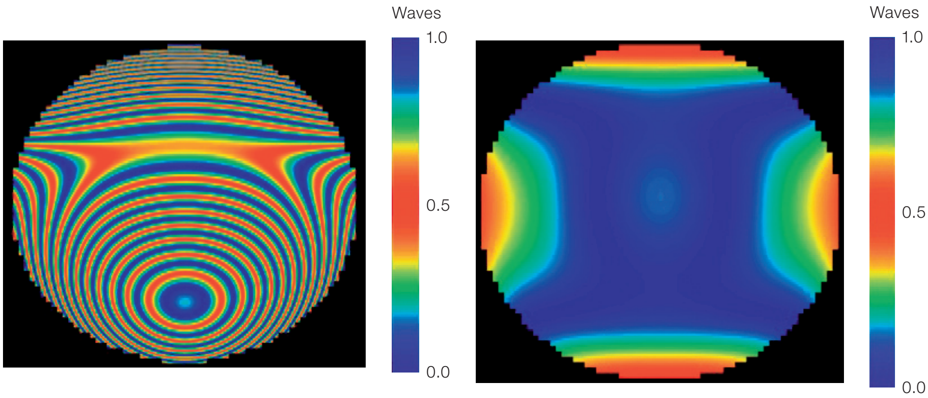

Figure 5: Wavefront aberrations in the laser guide stars. The five-mirror design (right) has a clear advantage over the Gregorian (left).

viewed off-axis. To work efficiently with the laser guide stars we will need to develop new generations of sensors that will allow us to centroid 'stars' that may be a number of arcseconds long. A number of programmes are under way both in Europe and the US to deal with this elongation. Potentially using pulsed lasers, rather than the current generation of continuous wave systems, may provide a very attractive way forward.

Even before the beam arrives at the post-focal adaptive optics systems, the E-ELT, as currently designed, will be able to deliver ground-layer adaptive optics corrections using as many as six laser guide stars and a number of natural guide stars. Ground-layer adaptive optics performance is expected to deliver an improvement of a factor of two or three in the encircled energy within 50 mas for objects within the inner five to seven arcminute field of view. Simulations show that beyond 10 arcminutes, no significant global improvement of the image quality can be expected. Beyond 10 arcminutes ground layer corrections no longer fix very much. Ground-layer correction may also feed more sophisticated post focal AO systems (e.g. multi-object adaptive optics). Laser tomography adaptive optics would also be available from the telescope systems.

Field of view

More field is always nice to have but only if it can be used effectively. As an excellent correction cannot be made across a large field of view, there is a break point where a smaller field telescope with better image quality will beat a larger field of view with poorer image quality. This is a complicated optimisation process that will require the details of the instrumentation to be folded into the design of the global systems. For the time being we are taking the recommendations of the ESE working groups and we retain the 10 arcminute field of view.

Instrument platforms

The E-ELT irrespective of design will have two Nasmyth foci and a Coudé focus. As some of the proposed instruments are expected to be rather large and complex, a gravity stable focus is to be provided even at the Nasmyth. Using a flat mirror and redirecting the beam downwards, an instrument can be installed at a location where it can rotate about the vertical axis and maintain a fixed angle with respect to gravity. To do this the telescope has to be able to change its focal length by relatively small amounts. This is routinely done at the VLT where the exchange from the true Ritchey-Chrétien f/15 focus at Nasmyth to the Cassegrain f/13.6 is performed without exchanging the secondary mirror, but rather by modifying the conic constant of the primary (using the active optics actuators) and refocusing the telescope. For the E-ELT, both the Gregorian and the five-mirror designs can support such a change of focal length. For the Gregorian design we would require that the secondary segments be re-aligned to modify the focal length of the telescope. In the five-mirror solution a natural zoom mode is offered by moving the tertiary mirror in the direction of the secondary. A wide-field Coudé focus can also be provided using this same zoom mode. However, as no requirement for a wide-field Coudé currently exists, a lens relay system is envisaged.

Hosting some of these enormous instruments requires a Nasmyth platform of considerable size. The recommendations of the ESE instrumentation working group have been taken into account and instruments weighing in at over 20 tons and with dimensions as large as 16 m on a side can be accommodated at the focus. More than one of these can be present on the platform at any given time.

Operational requirements

When considering such a large telescope, due attention needs to be paid to the various activities to be undertaken during operations. Exchanging more than one segment per day is likely and with only one E-ELT we will need to facilitate instrument exchanges. During 2006 the instrumentation team, in conjunction with the telescope and dome designers, has worked hard to find an elegant solution for the exchange of instruments. The proposed implementation involves a rail system and instruments that move on pallets. This is very much the same system as is used for the Nasmyth instruments at the VLT although there the pallet is used to carry the cable derotator and support the instrument during maintenance, while on the E-ELT it is expected that the pallet will be used at all times to support the instrument. To remove an instrument from the Nasmyth platform, a hydraulic elevator located in the dome lifts a Nasmyth extension with a matching rail system upon which the instrument can be moved and then lowered to the ground floor. Positions either side of each of the two Nasmyth platforms can be reached by rotating the azimuth of the telescope. Moreover, for the five-mirror design the same elevator can be used to access the secondary mirror for maintenance activities.

One of the prominent science cases calls for a high-resolution extremely stable spectrograph for radial velocity work. The E-ELT is the only one of the major ELT projects to provide a fully fledged Coudé focus. In lieu of the classical Cassegrain focus, the five-mirror design provides an intermediate focus that can be accessed by relatively small instruments to work in the thermal infrared. The implementation of this focus is not simple, as locating a full wavefront sensing capability at the side of the adaptive optics relay unit would be complicated. We envisage an open loop operation with the wavefront sensing performed at the Nasmyth focus. Such a solution will require much further analysis during the design phase of the project.

Although it is not seen as a requirement for the project, the idea of a full-field Atmospheric Dispersion compensator is very attractive for some science cases. The separating prisms solution, employed with great success for the FORS instruments at the Cassegrain foci of two of the Unit telescopes of the VLT, is a solution we are keen to redeploy. However, at the Nasmyth foci it is not possible to combine this solution while simultaneously limiting the introduced aberrations and decentre to sensible values. With a linear field of view of almost 2 m in diameter, a full-field ADC with a rotating prisms solution is also not plausible. The corrected field of view would be limited to the central five arcminutes. Somewhat more seriously the mechanisms for the ADC are likely to obstruct some of the field from where guide stars would need to be picked. In the five-mirror solution, a convenient location for the ADC can be found above the quaternary mirror where the beam is neither too slow nor too fast (f/4) and, with the deformable mirror to follow any introduced aberrations, can be corrected before the beam reaches the focal plane.

Trade-off between optical designs

A detailed trade-off between the Gregorian and the five-mirror design has been performed and presented to the ESO committees and in somewhat abbreviated form to the European community at the Marseille conference in December (see the article by Monnet, page 24). The industrial studies revealed that for a 42-m telescope the complexity, cost and schedule risk of a Gregorian deformable secondary mirror would seriously endanger the project. The deformable mirror of the five-mirror design is anything but straightforward. However, industrial proposals for its construction place it far from the critical path and a number of alternative solutions are available to the project. At 2.5 m in diameter, the quaternary is more than twice the linear size of the biggest deformable mirror currently under manufacture (the VLT deformable secondary mirror) and it would have at least five times, and possibly 10 times, the number of actuators. The 2.7-m field stabilisation mirror (M5) is also far from simple and in the next phase of the project significant attention is likely to be focused on both of the 'adaptive' mirrors. Another major challenge for the five-mirror design is the meniscus secondary mirror. Polishing such a mirror (actually the testing rather than the polishing) requires some innovative approaches. The Project Office has contracted with industry to investigate the matter and a solution, that would have the mirror ready within the timeframe for construction, has been proposed. The complexity of this mirror is comparable to that of the very large flat tertiary mirror of a classical design. A lot of emphasis will be placed on the mechanical support of this mirror and its behaviour in case of earthquakes during the Phase B design.

The advantages of the five-mirror design – in separating the field stabilisation function from the adaptive mirror, providing an instrument friendly focal plane and being laser friendly – make it a very attractive design. The two additional reflections of the five-mirror design are not expected to contribute dramatically to the total mirror count before the photons arrive at the instrumentation detectors. The Project Office will be looking into novel coatings currently under development that can further mitigate the effect of more reflections. Another significant advantage of the five-mirror design is that given the reasonable development timescales for the deformable mirrors, the telescope is well configured to take advantage of future enhancements in the technology of these systems. The cost of an upgrade of the deformable mirror of the five-mirror design to have a higher density of actuators, when this becomes available, would be comparable to that of a novel instrument and could be deployed in a similar or even shorter timescale. In the Gregorian case the cost and schedule of such an upgrade could be prohibitive.

The selection of the five-mirror design as the baseline does not exclude the evolution of many of the design choices. A reader with access to old copies of *The Messenger* may choose to search for the early ideas on the VLT and compare with the as-built observatory.

The ESO Council resolved that we should proceed into Phase B and we have already started our three-year design effort. During this phase we shall investigate the solutions that are in the baseline proposal and other concepts that may arise. Together with industry and institutes, we will fully develop the project with the aim to have a proposal for construction ready to be submitted to the ESO Council in late 2009 or early 2010. A seven-year construction timescale is foreseen.

During the Phase B, the FP6 ELT design study activities will be concluded. That work is expected to provide input on system aspects, control simulations, phasing methods, wind effects, dome designs, edge sensors, instrumentation, operations and other critical areas. The ELT Project Office is working closely with the FP6 programme to, as much as possible, avoid duplications. Within the FP6 programme, there is a site characterisation activity that we expect will start providing additional data on possible locations for the telescope. Currently no site is selected and therefore the project is evaluating the design for a variety of conditions.

Performance

A legitimate question that can be asked, when considering the performance of the E-ELT, is whether a smaller telescope using the same AO technology, e.g. the same number of actuators, would perform better since it could achieve higher Strehl ratios and correction at shorter wavelengths. We have analysed the trade-offs between collecting area and AO per-

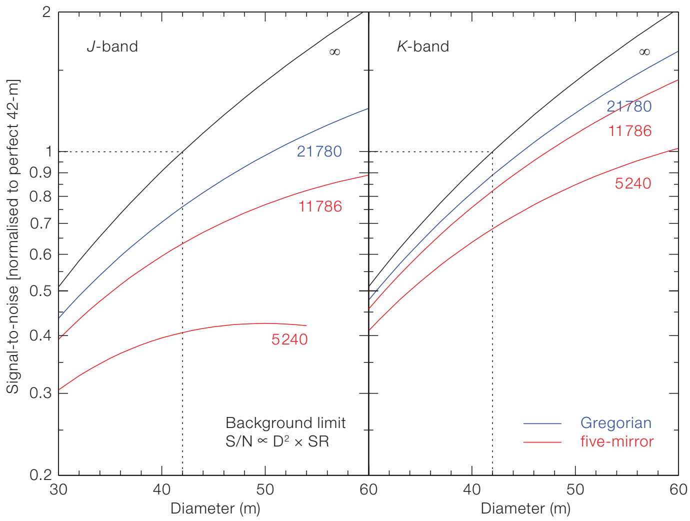

Figure 6: Signal-to-noise *versus* telescope diameter as a function of adaptive optics technology. The numbers of actuators for the options studied are indicated (from top to bottom): perfect AO; 30-mm pitch at the Gregorian secondary; 20- and 30-mm pitch at the five-mirror quaternary.

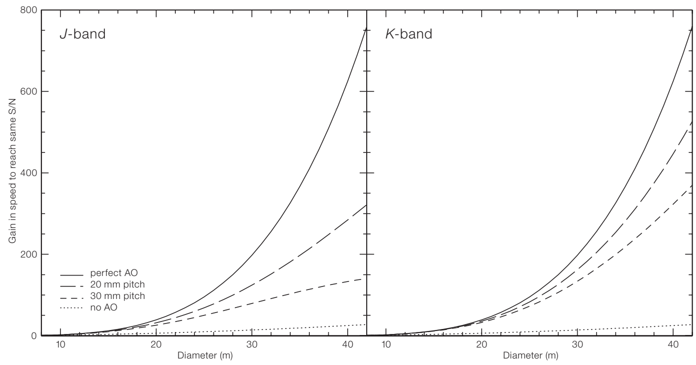

Figure 7: Gain in speed to achieve the same S/N compared with an 8-m telescope. The total number of actuators available at each diameter is kept constant and equal to the two technologies studied for the five-mirror solution.

formance based on the technology options explored by our industrial partners (see Figure 6). We find that in terms of sensitivity at near-infrared wavelengths, the gain in telescope diameter overcomes the loss of Strehl between e.g. 30 and 42 m. At around 50 m, the diameter gain in the *J*-band stops overcoming the loss of Strehl in the case of the lower actuator density technology. (Of course in terms of spatial resolution a larger telescope is always better). As pointed out above, the Gregorian has a better AO performance due to the higher number of actuators that can be accommodated by its larger adaptive mirror.

At shorter wavelengths there may indeed be an advantage of smaller telescopes that is more or less pronounced depending on the actuator technology considered. However, as explained above, the five-mirror design has a clear upgrade path to higher actuator density mirrors that will make the disadvantage a short-term one. Moreover, the requirements to perform AO at short wavelengths do not affect only the number of actuators, but also many other parameters, e.g. the bandwidth of the corrections and the power of the lasers to provide brighter guide stars. So it is not immediately obvious that a smaller telescope with the same number of actuators would be able to perform corrections at, say, optical wavelengths at the time E-ELT will start observing. For these reasons we conclude that the performance of a larger telescope in the range of interest is always superior.

Another way to look at performance is the ‘speed’, or the time necessary to achieve the same S/N on the same object for telescopes of different diameters. Even at ‘constant’ number of actuators, the gain of a 42-m telescope with respect to an 8-m telescope is enormous, achieving a value of more than 350 in the *K*-band even for the lower end of the actuator technology (see Figure 7). Although one could interpret this to mean that it would be possible to perform in one 42-m night the observations that take one year at an 8-m telescope (disregarding overheads and assuming identical instrumental configuration), the converse is not true, and the real power of a larger telescope is of course in the ability to detect fainter objects with better spatial resolution. It is also worth noting how much better the gain with diameter is when using AO compared with the gains in the seeing limit.

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