*The Institute of Space and Astronautical Science*
*Report SP No. 14, April 2000*

# Extremely Large Ground-Based Telescopes (ELTs): Performance Comparisons with 8-m class Space Telescopes

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(30 July 2000)

**Abstract:** Extremely Large ground based Telescopes (ELTs), with apertures between 25 and 100 m, are now being seriously studied by a number of groups. These proposals have several major technological barriers to overcome, but it seems probable that on the same timescale as space missions such as NGST and H2L2 (approximately 2010) one or more such telescopes may be becoming operational. Their performance, with atmospheric seeing correction by multi-conjugate adaptive optics (MCAO), will make them *dominant* in sensitivity for both imaging and spectroscopy for $1 < \lambda < 2.5$ μm and, in the larger aperures being considered, *competitive* in sensitivity for spectroscopy with resolution R $\geq$ 10,000 in the atmospheric windows at $\lambda\lambda$ 3-4, 8-13 and 20 μm. At all these wavelengths ELTs would have angular resolution far superior to that offered by any alternative facilities yet proposed.

## 1. INTRODUCTION

A decade ago there were approximately ten 4-m class ground based telescopes in operation with one 10-m telescope coming into service. Today there are perhaps 12 telescopes in the 4-m class while, remarkably, no less than 16 telescopes in the ~8-m ("VLT") class will soon be coming into operation. In space the now-veteran 2.4-m HST continues to generate a steady stream of dramatic results, while the proposers of its successor, the NGST, plan to hurdle the 4-m category completely and, at 8 metres aperture, to begin an era of space VLTs.

On the ground, meanwhile, the advent of the VLTs, and the prospect of NGST in space, have not stopped the progress of ambition. Even in the early '90s consideration of possible 25-m class ground-based facilities was developing (*c.f.*, for example, Owner-Petersen *et al.* 1994 and references therein) and technical studies progressing (*e.g.* Ardeberg *et al.* 1996). By 1996 also, serious exploration of alternative technologies (Bash *et al.* 1996) was producing cost estimates as low as $150M for some 25-m telescope designs, while current science drivers and technical options were being closely examined (Mountain 1996). Momentum has increased; the possibility of 100-m telescopes was soon explored (Gilmozzi *et al.* 1998). Even more recently,

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the critical technique of Multi-Conjugate Adaptive Optics (MCAO) (*e.g.* Beckers, 1989) has been demonstrated to be practicable (Ragazzoni *et al.* 2000). This promises (*c.f.* Ellerbroek & Rigaut 2000) to liberate Adaptive Optics (AO) from the limitations of classical single-guidestar techniques, which constrain fields of view (FOVs) to a few arcsec, across which the point-spread function (PSF) varies greatly. MCAO has the potential to provide, at least in the important NIR wavelength range from 1 to 2.5 $\mu$m, quite uniform, near-diffraction-limited, images over FOVs of order arcminutes.

The combination of MCAO with extremely large ($\geq$ 25 m) telescopes promises facilities of such power as to offer a discontinuous change in astronomical capability "comparable to that of the invention of the telescope itself" (Gilmozzi *et al.* 1998, section 6). In the rest of this article we discuss in more detail the design concepts being explored, critical technologies and technological challenges and the impact of MCAO. We summarise the performance of MCAO-equipped ELTs relative to that of a space telescope similar in size to the NGST (8 m) but at lower temperature (such that it has negligible intrinsic thermal background at any IR wavelength accessible from the ground).

We do not examine the science case for the facilities in question but note, first, that the initial drivers have been well set out by Mountain (1996) and that the recently-issued Decadal Survey in the US places a 30-m "Segmented Mirror Telescope" at the top of its wish-list for ground-based facilities.

## 2. *ELT* CONCEPTS UNDER DISCUSSION

### 2.1 Hobby-Eberly as a 25-m ELT

Amongst current proposals for a leap beyond the 8-m class of ground-based telescopes, the least expensive-looking are those originating from the team associated with the $\sim$ 9.3m Hobby-Eberly Telescope (HET) for a 25-m using the same design principles (Bash *et al.* 1996 and references therein).

The HET is a minimum-cost VLT currently being commissioned in Texas and likely soon to be cloned in South Africa. It and its proposed ELT offspring use a design resembling that of the Arecibo radio telescope, with the segmented, spherical primary mirror tilted at a fixed zenith angle and therefore subject to a constant gravity vector. Rotation is in azimuth only and is employed only for acquisition: a mobile focal plane feed assembly, providing spherical aberration correction, tracks targets for 45 minutes or more as the entrance pupil moves across the stationary primary mirror.

The Hobby-Eberly Telescope was built (though not yet commissioned) for the remarkably low cost of $\sim$ \$14M, and the team estimate the total cost of their scaled-up 25-m ELT version at around \$250M (Sebring *et al.* 1998)

### 2.2 The 30-m California Extremely Large Telescope (CELT) proposal

The builders of the highly successful Keck telescopes are currently studying proposals for a 30-m successor. Initial concepts were presented by Nelson & Mast (1999) and a more recent outline of the design concepts was given by Nelson (2000). This differs from the HET-clone and OWL (see below) proposals in several ways, but in particular in adopting a non-spherical primary for a Ritchey-Chretien design, the proposers believing that the complications of fabricating large numbers of aspheric elements can be overcome inside an attainable budget (*c.f* Mast, Nelson & Sommargren, 2000).

This proposal explicitly includes the capability to deliver a large ($\sim$ 20 arcmin) FOV in order to permit seeing-limited ($\sim$0.″5 resolution) multi-object spectroscopy as well as near-diffration-limited MCAO operation.

### 2.3 50-m Telescopes: Swedish designs for an ELT and the Maximum Aperture Telescope (MAXAT)

The arguments outlined by Mountain (1996) have tended to drive a number of studies in the direction of a facility significantly larger then the 25-m to 30-m concepts outlined above. Both the Swedish group (*c.f* Ardeberg *et al.* 1996: 25 m; Ardeberg, Andersen & Owner-Petersen, 1998: 25-50 m; Gontcharov & Owner-Petersen, 2000: 50 m) and the US-based studies of MAXAT (Maximum-Aperture Telescope are following this trend. The selection of 50 m for the aperture (at least as a goal) is also in significant part driven by scepticism about the ultimate practicability of building a 100-m facility such as is proposed by the OWL study team (next section).

Nevertheless many design aspects of the 50-m and 100-m proposals are similar and a great deal of synergy between the teams is occurring.

### 2.4 European ambitions: the OverWhelmingly Large (100-m) OWL

As noted above, the ambitious proposal for a 100-m facility (OWL) was first put forward by Gilmozzi *et al.* in 1998. In recent incarnations OWL has evolved through a number of possible optical configurations, most assuming a 100-m spherical primary mirror and a 15- to 25-m spherical (Gilmozzi *et al.* 1998) or flat segmented secondary (*e.g.* Brunetto, Koch & Quattri, 1999). Recent developments include a comprehensive examination of optical design and practicality issues for such a facility and its instrumentation at the UK Astronomy Technology Centre (Atad-Ettedgui *et al.* 2000). This work has highlighted some of the difficulties in providing a realistic "seeing-limited" capability for so large a telescope, amongst other instrumental issues, and also the potentially important problem of the degrading effects of atmospheric dispersion, even in the NIR, for image sizes of a few milli-arcsec.

An active study group under the aegis of the European Southern Observatory (ESO) (*c.f.* Dierickx & Gilmozzi, 2000) is continuing the earlier design work. The telescope is currently envisaged as being partly subterranean, with the primary mirror approximately at ground level, and much of the structure below ground level when observing near the zentih. The telescope would have the ability to tilt its optical axis down to the horizontal to allow engineering on the topend and to permit it to be protected in a roll-away structure when not in use.

Informal cost estimates for this facility suggest that it can be built for of order \$$10^9$; but as noted, scepticism about such estimates is in part responsible for the concentration of several groups on a 50-m alternative.

## 3. ENABLING TECHNOLOGIES AND CHALLENGES

Technological issues are obviously of the utmost importance for the realisation of a working ELT. Achieving the "discontinous change in astronomical capabilities" of Gilmozzi *et al.* 1998 presupposed that all of these can be met and mastered. We here identify only a salient selection.

### 3.1 Smart Structures and the management of deformations

The vast and partially-exposed structure of an ELT will need to be able to correct, at high bandwidth, for both solid-body and internal perturbations, both of which will be inevitable consequences of exposure to wind.

The OWL and MAXAT teams have naturally taken these issues particularly seriously, as neither can realistically expect to house their vast brainchildren in permanently protective structures (which *have* been assumed in their baseline designs by proponents of the smaller CELT and super-HET concepts). Considerable discussion is available in the literature and in circulation: Ardeberg *et al.* 1996 discuss in detail the deformations of a "point design" for a 25-m facility; Brunetto, Koch & Quattri (1999) examine, *inter alia*, the eigenmodes of a point design for OWL.

This issue may overlap into the management of the optical system for AO purposes, as the frequency and actuation demands are not too dissimilar: the same effective precison is required of the telescope structure and of its optical components, which will be subjected to the same disturbances (variable wind loads). It seems certain that sophisticated laser metrology systems will be needed to determine and monitor the corrections required, while high-bandwith actuators of a variety of dynamic ranges and resolutions need parallel development.

### 3.2 Production of mirror segments

This potentially major issue is already attracting serious study, as the sheer acreage of optical surface required is such that an efficient production system must commence work well in advance of the telescope's construction if its aperture is to be even partially filled at the time of commissioning. Thus considerable (and illuminating) discussion of production techniques in incoprporated in the proposal-paper for OWL (Gilmozzi *et al.* 1998) which at that time was to include 2058 hexagonal spherically-curved segments, each 2 m across.

Gilmozzi *et al.* focus on various fused silica derivatives and ceramics, and aluminium, as potential materials. Surprisingly, a new fabrication approach may make SiC a serious option. These authors present some ideas for the development of a "production line" process for glass-ceramics such as zerodur.

Fabrication by replication may also have the potential to achieve the high production rates required it the telescope is to be completed in a reasonable time. Variants of conventional polishing techniques, again aimed at a production-line approach whereby four segments are processed at once, were also investigated.

A discussion of the issues involved in fabricating aspheric segments for CELT is given by Mast, Nelson & Sommargren (2000). Considerations of cost and speed lead them to select a design incorporating $\sim$1000 segments, each 50cm on a side ($\sim$1m across) and 45mm thick. Polishing would be done to a spherical target surface after the blank has been mechanically distorted so that release of stress after completion gives the desired hyperbolic form. Final ion figuring and fine-tuning using a Keck-style warping harness are proposed.

### 3.3 Multi-Conjugate Adaptive Optics

As indicated above, MCAO is likely to be the critical technology without which ELT projects may simply lack the attraction necessary to carry through to completion. That it can be made to work as proposed was demonstrated by Ragazzoni *et al.* 2000.

In brief, this approach utilises several laser guide stars (LGSs: probably generated by exciting the 90-km sodium layer; 4 to 9 may be required) to eliminate the "cone effect" which limits the performance of classical AO using a single LGS, and to allow a small number (2-5 in current studies) of wavefront sensors, conjugated to selected altitudes, to sample the entire volume of air through which the incoming wavefronts must pass. The technique consequently allows a much larger FOV to be corrected than is possible with a single LGS.

Several natural guide stars are also required to eliminate problems associated with tip-tilt effects and aliases (*e.g.* anisotropic defocussing, astigmatism). Because these are tip-tilt effects the isoplanatic angles for the NGSs are large (in proportion to the telescope aperture) and this aspect of the overall design is likely to scale very benignly with increasing aperture.

At present it appears likely that at $\lambda \geq 1$ $\mu$m Strehl ratios around 50% can in principle be achieved over fields of view $\sim 1'$ on a 30- 50-m telescope. Strehl ratios of order 80% should be attainable at 2 $\mu$m with this FOV; indeed at this wavelength Strehl ratios around 50% may be attainable over fields approaching $3'$ (B.Ellerbroek, personal communication).

While the basic performance scales well with aperture there are technical issues of which this is not true. Because of perspective effects the power requirements of the lasers for the LGSs scales as the square of the aperture: since the currently available technology is not quite adequate for the requirements of an 8-m telescope large strides are needed. Scaling of the computer power required to manage the AO system, using current methods, is expected to rise as the 4th power of the aperture, and even Moore's law may not rescue the situation in time. However new computing techniques *may* change the scaling law to $DlogD$, so it may be that this technology can be matched to realistic requirements on the required timescale. Nevertheless its attainability on a 100-m telescope is quite a long way from credible demonstration.

## 4. *ELT* OPERATING MODE CONFLICT: WITH OR WITHOUT SEEING?

A critical issue in determining the admissible science drivers of an ELT is the degree to which seeing-limited observational strategies shall be allowed to affect the design. Thus, the current proposals for CELT are explicitly intended to provide a wide field, in particular for multi-object spectroscopy, while the MAXAT group tends to take the position that seeing-limited use is just a possible fringe-benefit of the overall design, which is driven entirely by expoiting MCAO.

The programme proposed by Mountain (1996) for initial definition of the science goals of an ELT is the need to obtain spectoscopy of *all the galaxies in the Hubble Deep Fields.* This can be achieved by a 50-m telescope operating near the diffraction limit over armin FOVs: indeed, by using Integral Field techniques spectra of the *components* of such galaxies should be obtainable. However, objects which are more thinly distributed on the sky could in principle justify a much wider field, to be covered *at the seeing limit* by a multi-object spectroscopic system.

MCAO may offer Strehl ratios $> 50\%$ over $\sim$ arcmin fields at $\lambda = 2$ $\mu$m, perhaps 30 times higher than for a seeing-limited image. The speed with which the telescope can secure a given observation of a faint source is proportional to the *square* of this ratio: the ELT should therefore be *almost a thousand* times faster for faint-object spectroscopy in MCAO mode than in seeing-limited mode. Thus 100 widely-scattered targets would be observable *several times* faster in MCAO mode than in seeing-limited mode with a multi-object instrument, even allowing acquisition overheads.

This result is strongly aperture-dependent. Barden and Parks (1999) derive a relative speed advantage for an MCAO-equipped *30-m* ELT of only 100 relative to the seeing-limited case, so overheads would make serial observation of 100 objects significantly *slower* with the MCAO than their (parallel) observation with a MOS system. This is because speed goes as the 4th power of aperture under these (approximately diffraction-limited) observing conditions, giving a 50-m an 8-fold speed advantage over the 30-m.

However all else is by no means equal: the seeing-limited facility must fit several hundredths of a square arcsec onto a typical detector pixel. For a 50-m telescope to squeeze a $0.''2$ angular FOV onto a 20 $\mu$m-square *physical* pixel a final f-ratio of 0.41 is required (*c.f.* Attad-Ettedgui *et al.* 2000, section 6.1.1). It is generally considered that designs having final f-ratios $< 1$ are unlikely to be realisable. Substantial oversampling of the delivered images will necessarily have to be accepted: a 50-m with final f/ratio of 1 would have $\sim 6$ pixels across the image FWHM, resulting in considerable performance losses for spectroscopy.

Currently it is difficult to see how a 50-m class ELT can be efficiently used in a seeing-limited mode, unless this is viewed as a backup mode in which loss of performance can be accepted in order to stay in operation. Nevertheless this debate is quite unresolved, and will probably remain so until a clear and hard-nosed set of scientific objectives (*c.f.* the "Design Reference Mission" of the NGST) are examined in detail.

## 5. PERFORMANCE OF A NEAR-DIFFRACTION-LIMITED *ELT* RELATIVE TO A COLD TELESCOPE IN SPACE.

Gillett & Mountain (1998) made initial performance comparisons between a cold space-based 8-m telescope and a ground-based 8-m facility with adaptive optics. They emphasised the substantial advantages, because of lower backgrounds, of the space-based facility. However they pointed out that, especially for moderate to high-resolution spectroscopy, the advantage of the telescope in space was very subject to assumptions about detector performance, and at some wavelengths could vanish with a relatively small reduction in aperture.

Oschmann *et al.* (1999) developed this comparison to cover 20, 30, 50 and 100-m ELTs. They make conservative assumptions about imaging performance, based on early experience with Adaptive Optics on Gemini: a falloff of AO performance at short wavelengths is assumed, such that image size (50% encircled energy diameter) is effectively $2.1 \times$ (diffraction limit) at $\lambda = 1.0\ \mu$m, scaling to $1.1 \times$ (diffraction limit) at $\lambda = 2\mu$m and longer wavelengths.

They adopted the detector performance characteristics, extrapolated from present-day achievements, used by Gillett & Mountain (1998), and assumed "typical" Mauna Kea atmospheric properties.

The performance of the ground-based ELTs was compared with that of a (cold) 8-m telescope in space, at 1AU from the sun, for imaging and for spectroscopy, assuming 10,000s total exposures assembled from realistic on-chip exposure times in the face of cosmic ray hits and other limiting factors. The results (from Mountain, 2000, personal communication) are summarised in Table 1.

## 6. CONCLUSIONS

### 6.1 Imaging

Table 1 shows that in the 1.25, 1.6 and 2.2 $\mu$m windows the ELTs are at least competitive, and for the most part well ahead, in imaging performance. The huge gains with aperture for operations in the diffraction-limited regime are particularly apparent from the performance of

Table 1: $S/N$ of ELTs with apertures of 20, 30, 50 and 100-m relative to a cold 8-m space telescope. (See text for details of models.)

| $\lambda$ ($\mu$m) | Imaging (R=5) | | | | Spectroscopy (R=$10^4$) | | | |
|---|---|---|---|---|---|---|---|---|
| | *20-m* | *30-m* | *50-m* | *100-m* | *20-m* | *30-m* | *50-m* | *100-m* |
| *1.25* | 1.37 | 2.4 | 6.7 | 23.0 | 3.8 | 6.0 | 10.4 | 20.2 |
| *1.6* | 0.82 | 1.5 | 4.1 | 15.0 | 3.8 | 6.0 | 10.4 | 20.1 |
| *2.2* | 0.61 | 1.4 | 4.0 | 14.1 | 3.0 | 4.9 | 8.7 | 17.0 |
| *3.5* | 0.024 | 0.053 | 0.146 | 0.57 | 0.32 | 0.71 | 1.9 | 7.2 |
| *4.9* | 0.003 | 0.013 | 0.036 | 0.13 | 0.028 | 0.063 | 0.18 | 0.66 |
| *12* | 0.008 | 0.019 | 0.052 | 0.20 | 0.058 | 0.132 | 0.36 | 1.42 |
| *20* | 0.003 | 0.021 | 0.058 | 0.22 | 0.031 | 0.071 | 0.20 | 0.76 |
| *25* | 0.003 | 0.021 | 0.058 | 0.22 | 0.026 | 0.058 | 0.16 | 0.61 |

the 100-m relative to the 20-m facility. It must be remembered too, that this performance goes hand in hand with *a major advantage in spatial resolution.*

- ***In the near-IR*** *the ELTs are competitive or dominant in imaging sensitivity.*

- ***In the Thermal-IR*** *the ELTs are completely outperformed in sensitivity and (especially) speed by the cold 8-m space telescope.* (Note that *speed* varies as the *square* of the $S/N$).

### 6.2 Spectroscopy

It is immediately evident from Table 1 that all the ELTs *dramatically outperform* the space telescope in the 1.25, 1.6 and 2.2 $\mu$m windows for spectroscopy: even the 20-m is an order of magnitude faster than the 8-m in space for spectroscopy at 2.2 $\mu$m. The 50- and 100-m facilities outperform the space telescope at $\lambda = 3.5$ $\mu$m as well. Indeed the 100-m is *competitive* for spectroscopy at all the wavelengths considered, while the 50-m delivers a useful fraction of the performance of the cold space 8-m even at $\lambda\lambda$ 5 to 25 $\mu$m.

It must be noted, too (*c.f.* Gillett & Mountain 1998) that a ground-based facility has a natural advantage in keeping up to date in technological development. This means that the numbers in the Table will grow with time after launch of the space telescope; or, in fact, with lapse of time after its instrument design is frozen (unless the space facility occupies an orbit accessible to servicing missions and is designed to be upgraded).

- ***In the near-IR*** *(to 2.2 $\mu$m) the ELTs dramatically outperform the 8-m space telescope for spectroscopy.* (The larger apertures outperform the cold telescope out to $\lambda = 3.5$ $\mu$m)

- ***In the Thermal IR*** *the larger ELTs* ***may*** *be - or become - competitive with the 8-m space telescope for spectroscopy in all the atmopheric windows.*


## Acknowledgements

TGH is grateful to Matt Mountain and Jim Oschmann for a vigorous introduction to the issues surrounding the development of the ELT generation of telescopes, and to François Rigaut and Brent Ellerbroek for a gentle introduction to the arcana of MCAO. He particularly thanks CMM for access to the results of his sensitivity calculations in advance of their publication and for a critical reading of a draft of this paper.

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