Progress on the California Extremely Large Telescope (CELT)

Jerry Nelson*
University of California Observatories
University of California, Santa Cruz, CA

ABSTRACT

The California Extremely Large Telescope (CELT) is a joint project of the University of California and the California Institute of Technology to build and operate a 30-meter diameter telescope for research in astronomy at visible and infrared wavelengths. The current optical design calls for a primary, secondary, and tertiary mirror with Ritchey-Chretién foci at two Nasmyth platforms. The primary mirror is a mosaic of 1080 actively stabilized hexagonal segments. This paper summarizes the recent progress on the conceptual design of this telescope.
Keywords: CELT, optics, observatory, telescope

1 INTRODUCTION

The California Extremely Large Telescope (CELT) is a joint project of the University of California and the California Institute of Technology to build and operate a 30-meter diameter telescope for research in astronomy at visible and infrared wavelengths. The current optical design calls for a primary, secondary, and tertiary mirror with Ritchey-Chretién foci at two Nasmyth platforms. The primary mirror is a mosaic of 1080 actively stabilized hexagonal segments. The Project has been briefly described earlier (Nelson, 2000). In this paper we review the current status of the design including the adaptive optics (AO) that will bring diffraction-limited imaging, and scientific instruments that will be needed for both seeing-limited and diffraction-limited observations. Many aspects of CELT are described in CELT Report No. 34. The report is posted at the CELT website: http://www.ucolick.org/~celt/

1.1 What is CELT?

The University of California and the California Institute of Technology partnered in the 1980's to create the Keck Observatory, a system of two 10-m telescopes. We are now partnering to design a 30-m telescope that will allow us to carry out state-of-the-art observations ranging from observations of galaxies during the first epoch of star and galaxy formation to direct observations of planets around other stars. By making key economies relative to the Keck Observatory, and by adding a powerful adaptive optics (AO) system, CELT should far surpass the power of the Keck telescopes (currently the most powerful in the world) at a cost much lower than a simple extrapolation of the Keck Observatory would suggest.

A conceptual design study (Phase 1) has been underway for two years and has led to a design that is feasible and buildable. Although this design has shown feasibility, in the next design phase (Phase 2) we will re-examine most assumptions in this design and optimize the facility for both cost and performance. Phase 2 will also include significant effort to carry out technology development and related risk reduction. This should lead to a design with reduced technical risk and a reliable cost estimate. Following this design phase we plan to construct (Phase 3) and operate the observatory.

At the end of Phase 1 (May 2002) the Universities held an external review. The review committee recommended to the Universities that they proceed with the design and construction of CELT. Of course, doing this requires significant funds, and these funds are not yet available at the time of this writing.

1.2 Requirements Summary

The scientific case for CELT is given in CELT Report 34, and is summarized by Ellis (2002). The scientific opportunities have led to requirements for CELT that are summarized here.

- Aperture: filled, fully steerable 30-m telescope

* jnelson@ucolick.org 1-831-459-5132

- Field of view: 20-arcminutes with 0.5 arcsecond images (seeing-limited observations)
- On-axis visible light image quality: 0.14 arcseconds (FWHM)
- AO: low order AO and multiconjugate AO, rms wavefront goals down to 75 nm rms
- Zenith angle for observing: 0° to 65°
- Observing wavelength range: 300 nm to 30 µm
- Instrument support: Two 15x30m Nasmyth platforms

1.3 Design Summary

The basic optical design is a Ritchey-Chretien, with a f/1.5 primary and a final f-ratio of f/15. This design gives a 20-arcminute field of view with <0.5-arcsecond image quality, and a 3.9-m diameter secondary mirror. For simplicity, all scientific instruments will be located on the Nasmyth platforms. The steerable tertiary mirror is in front of the primary and allows multiple instruments to be accessed with only 3 reflections.

We are currently using a reference optical design for CELT. In the next design phase we will make a quantitative trade among costs to define the final optical design. The reference design calls for a Ritchey-Chretién system with a tertiary flat mirror to position a focus at either of two Nasmyth platforms. There will be no prime or Cassegrain foci. The primary mirror is a mosaic of 1080 hexagonal, actively stabilized, segments each with a circumscribed radius of 0.5 meters. The primary segmentation is shown in Figure 1. Diffraction effects from segments are described by Troy and Chanan (2002). The design calls for sets of 19 segments to be mounted on a cluster frame, and the frames to be mounted on the mirror cell. The following parameters define the optics. The optical layout is shown in Figure 2. An optical alignment procedure is described by Mast et al (2002).

Primary radius of curvature	k1 = 90 meters
Primary conic constant	K1 = –1.002837
Secondary radius of curvature	k2 = –12.4242 meters
Secondary conic constant	K2 = –1.524
Back focal distance	e = 16.5 meters
Primary Diameter	D1 = 30 meters
Number of Hexagonal Segments	Nseg = 1080
Segment Circumscribing Radius	a = 0.5 meters
Segment thickness	h = 0.045 meters
Field of View Radius	= 600 arc seconds

Parameters derived from these include

Primary focal length	f1 = 45 meters
Secondary focal length	f2 = –6.2121 meters
Final focal length	f = 450.0 meters
Primary F-ratio	F1 = 1.5
Final F-ratio	F = 15.000
Magnification = f/f1	m = 10.00
Primary-secondary distance	d = 39.41 meters
Δ	e / f1= 0.367
plate scale	p = 2182 microns/arc second

The telescope structure is a space frame with the elevation axis in front of the primary. Medwadowski (2002) is responsible for design of the structure. The upper truss that supports the secondary is designed to have minimal light blockage of the primary and minimal wind cross section to reduce the coupling to winds. For wind and weather protection, a dome will be required. This has an 84-m inside diameter and a 90-m outside diameter.

An overall view of the telescope in the enclosure is shown in Figure 3. The telescope structure has been designed and analyzed, but the dome is not designed in any detail. Figure 4 shows the telescope and dome from the side. This indicates the relative proportions of the various components. Figure 5 shows the telescope as seen looking down along the optical axis. The modest blockage of the primary is seen along with the relative sizes of the Nasmyth platforms.

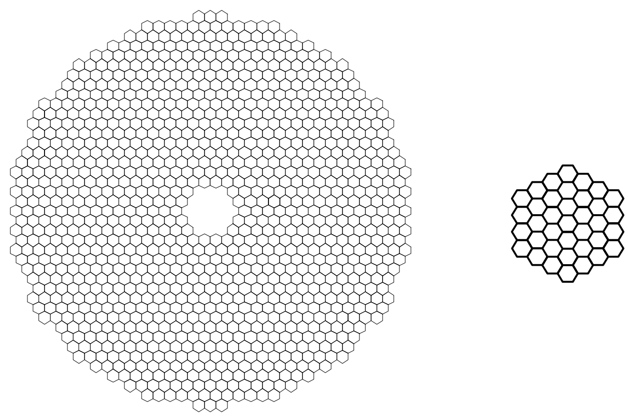

Figure 1. The primary mirror segmentation showing 1080 segments. The Keck primary mirror is shown to the same scale for comparison.

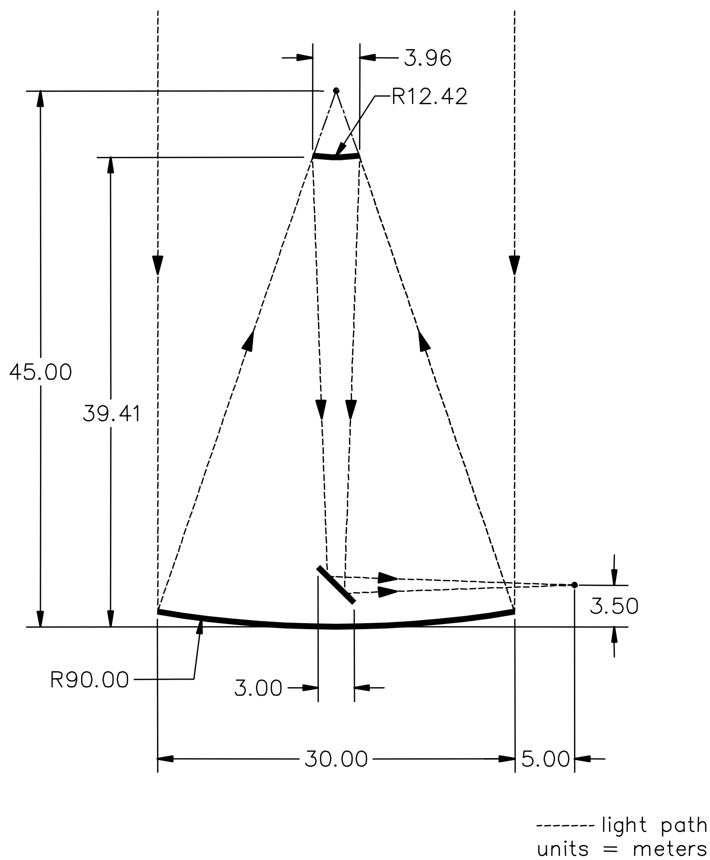

Figure 2. Optical layout of CELT showing the primary, secondary and tertiary, and the Nasmyth focus.

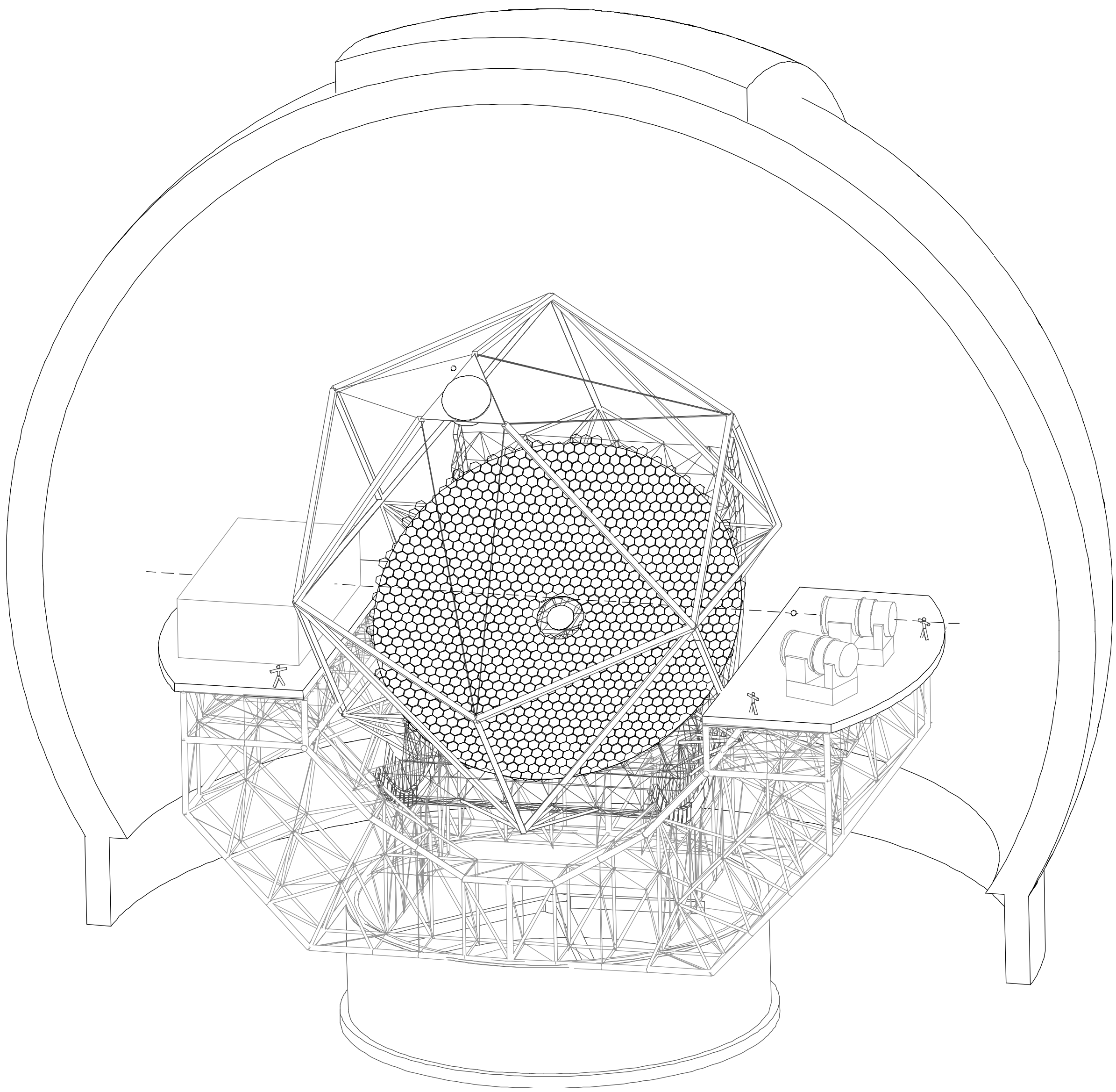

Figure 3. A view of CELT inside the enclosure. The Nasmyth platforms and schematic instruments are indicated.

2 MAJOR PROJECT ISSUES

As the Project enters Phase 2, there are a number of key issues that will be addressed. These issues often interact with each other, so they must be addressed simultaneously, rather than in series. Underlying these major issues is the work on technology. A number of technical issues must be addressed as risk reduction activities, either to establish the feasibility of an item or to test that it can be made economically and reliably.

The first major issue is the optimization of the optical parameters. Although we believe that the given design is feasible, the focal length of the primary is a strong driver of the details of the structural design and of course the size and cost of the enclosure. Thus, we will explore the consequences of altering the primary mirror focal length, the size of the secondary, the location of the elevation axis, and the segmentation geometry of the primary.

The difficulty/cost of fabricating mirror segments is likely to depend on the asphericity of the segments. The maximum segment asphericity varies as the square of the segment diameter, the square of the off-axis distance of the segment, and inversely as the cube of the primary focal length. Thus segment size and primary focal length will strongly drive the segment polishing difficulty. Engineering evaluation of this issue must be carried out soon. Figure 6 shows the segment asphericity as a function of segment size and primary focal length. Keck segments had a maximum asphericity of about 113 µm. The initial GSMT baseline (Strom et al, 2002) has a maximum asphericity of about 100µm. The CELT conceptual design has deliberately reduced the asphericity to about 20µm.

Segment size also strongly impacts the passive support difficulty. Gravity driven deflections vary as the segment diameter to the 4^{th} power and inversely as the square of the segment thickness.

Segment alignment in the primary will also be a challenge, as its tolerances vary inversely as the asphericity of the segments.

The primary segment positions (piston, tip, tilt) will be actively controlled, with three actuators per segment. Edge sensors will measure the relative heights of all adjacent segment pairs. There are approximately 6 edge sensors/segment. Thus the number of actuators and sensors have a strong impact on the complexity and reliability of the control system.

Once the engineering studies and component prototyping and testing have been carried out, it should be possible to understand the tradeoffs and optimize the optical design. Many issues are involved in this, and making this optimization is a major objective of Phase 2.

The second major issue is to better understand the effects of wind loads on the telescope. The wind speed statistics as well as its turbulent structure will depend on the actual site selected, hence the problem is not completely defined at this time. However, wind loads on the top of the structure may lead to objectionable image motion. This may drive the design of the active secondary positioning system, and will be critically dependent on the structural design of the telescope. The wind loads may also have an impact on the primary mirror, causing relative segment motion that could be objectionable. Thus a careful study of the wind dynamics and its interaction with the dynamical properties of the entire telescope is needed. The structural design will need to be carefully optimized to reduce the impact of wind loads, and efforts to maximize the lowest natural frequency will be important.

The third major issue is AO. CELT will be significantly empowered by its AO system. The current AO goals for CELT are not achievable with AO systems or components that can be purchased today. Thus AO for CELT will require significant development of key components. In addition, due to its complexity, the basic system modeling of AO has not yet been carried out for CELT. As a result, we do not yet know the AO system design. Issues such as the impact of number and location of laser beacons on final image quality and field of view are not yet well established. Deformable mirrors will be needed that are not available, and their number and size needs to be determined by optical and system design.

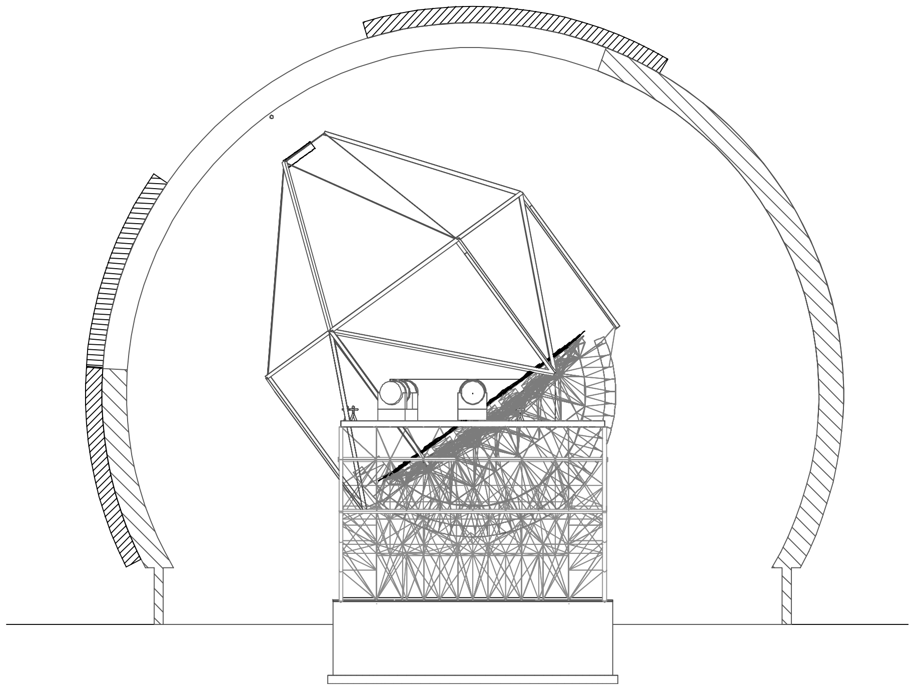

Figure 4 A side view of the telescope and dome. Note the elevation axis in front of the primary. The shutter has three parts to provide maximum wind protection at all observing elevations. Also note the very small wind cross section of the upper structure.

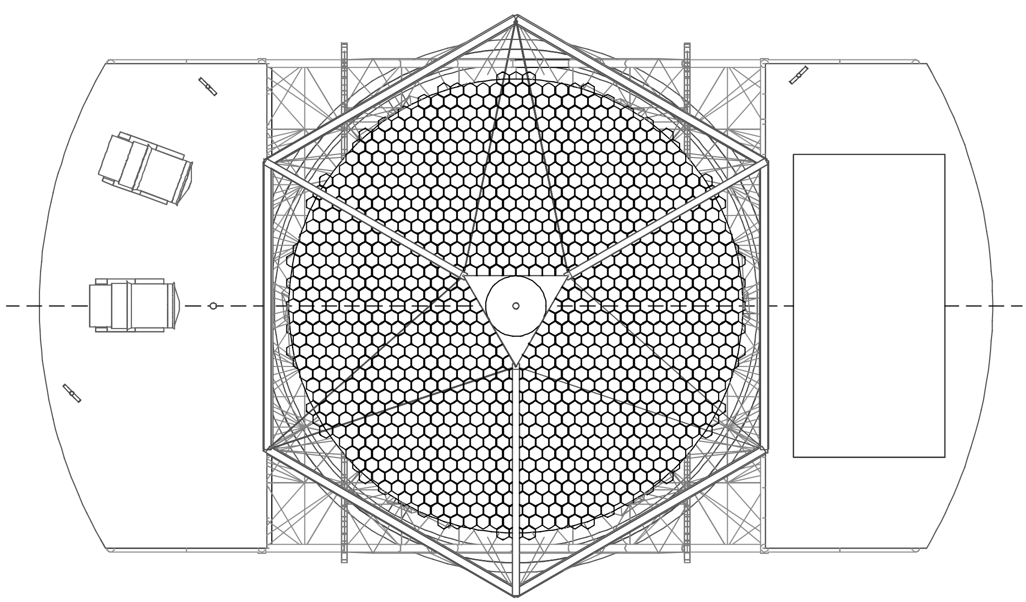

Figure 5. This plan view of the telescope shows the upper tube with its blockage of the primary and the Nasmyth platforms with typical instruments placed on them.

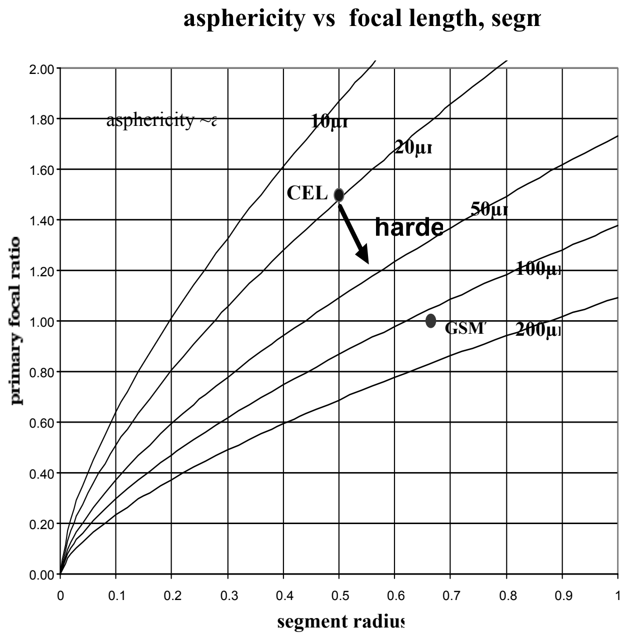

Figure 6. Curves of constant segment asphericity are drawn as functions of segment size and primary focal ratio. The present CELT design and the GSMT design are noted.

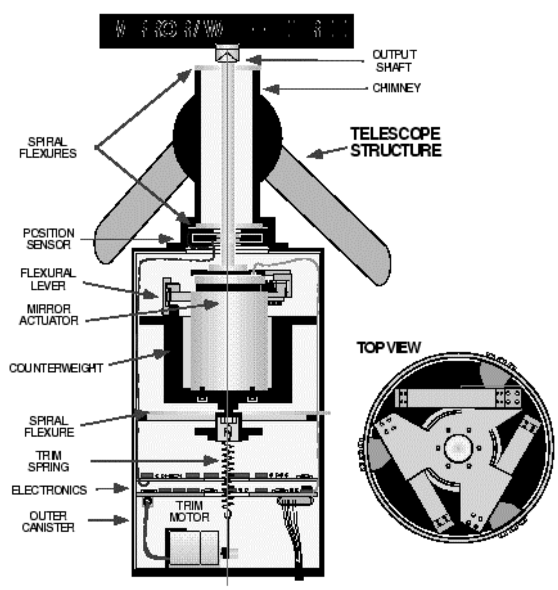

Figure 7. Prototype CELT actuator schematic

The fourth major issue is the site. We believe that the process of site selection is in the critical path for CELT. Finding a suitable site will be difficult and worldwide site evaluation has begun. The choice of site may have significant impact on the telescope design and may also impact the scientific capabilities of CELT, since seeing quality, clear nights, water vapor levels, temperatures, and vertical turbulence profiles are all important and differ from site to site. A description of the site work is given by Schoek et al (2002).

3 PRIMARY MIRROR

As indicated, the optimization of the primary mirror design is a key issue. The primary mirror is likely to be expensive to fabricate and potentially a major maintenance issue. Segments are defined by the primary focal length, the segment radius, and the segment thickness. The conceptual design has k1 = 90m, a = 0.5m, h = 0.045m. The segment passive support complexity depends on the segment diameter and thickness. The active control system complexity depends on the number of segments.

3.1 Segment fabrication

The actual fabrication of the segments will be costly and depend on the segment size and asphericity. We have not yet made any prototype segments, but in Phase 2 will do so. Currently we expect that planetary polishing of the segments, stressed into spherical shape, will be the most economical approach. This is a generalization of the approach successfully used for Keck segments (stressed mirror polishing) and the HET (planetary polishing of spheres). Analysis suggests that a circular mirror blank, 5% oversized, and attached to a stressing fixture at 24 points will suffice. After polishing, the mirror will be cut into the desired hexagon, re-tested, and ion figured to its final optical surface. This final stage will allow for correction of any warping that occurs from the cutting. Although this is likely to be the most economical approach, we will invite commercial vendors to suggest alternate approaches that may better suit their capabilities.

3.2 Passive support

The segments must be supported against gravity, and this must be done so that the optical surface deformation is acceptably small. The complexity of such a passive support will grow as $\sim a^4/h^2$. Steve Gunnels (Gunnels, 2001) has produced a preliminary design of such a support that meets our needs. The axial support consists of an 18-point whiffletree arrangement glued onto the back surface of the mirror, and attaching to the three positioning actuators. The maximum gravity driven deflections are about 6nm rms. The lateral support system consists of a counterweighted arm that is attached to the back surface of the segment.

As has been indicated above, the smaller segments of CELT relative to Keck allows us to both make the segments thinner and allow the simpler support (18 support points for CELT, 36 support points for Keck). With fewer support points, the accuracy requirements of the support system fabrication are also reduced. This will allow us to significantly reduce the cost of the passive support.

3.3 Active Support

Three actuators to provide piston, tip and tilt positional control will support each segment. By using relatively small segments and a relatively slow primary, the other three degrees of freedom that define a segment can be passively controlled by proper installation accuracy. However, the active system will require 3240 actuators that must work reliably, have the needed operating range (~ 2mm) and smoothness (~ 10 nm), and be economical. We have chosen to measure the relative segment positions by use of edge sensors, similar to the ideas of Keck. This suggests we will need 6204 edge sensors for CELT, where Keck had 168. These devices must be reliable, economical, and have excellent noise and stability (~ 5 nm). Finally, it is essential that the noise propagation from the sensors to the actuators and mirror segments is well understood, and adequate to allow us to maintain the excellent mirror quality we need for CELT.

We have surveyed a variety of potential actuator options, including two-stage systems. At this time, a single-stage actuator appears feasible, and we have produced a design and prototype of a voice coil actuator that may meet our needs. The actuator is described by Lorell etal (2002). The actuator is all flexural (except for a simple force offloading motor), and the motive force is a voice coil. The actuator is basically a force actuator, with a high-speed control system using an internal capacitive sensor to control the actuator position. This actuator has the promise of being very reliable and significantly less expensive than the Keck actuators. Figure 7 shows the prototype actuator design.

The edge sensors we are proposing for CELT are conceptually similar to the Keck sensors (Figure 8, edge sensing, capacitive sensors) but have significant advantages over the Keck sensors. The proposed sensors will be bonded onto the edges of the segments, thus avoiding the expensive mechanical construction of the Keck sensors, and also avoiding the interlocking nature of the Keck sensors. The interlocked sensors add complexity to segment handling and replacement. The new sensors offer the same sensitivity as the old ones, and through their tilt sensitivity also provide adequate sensitivity to global focus or curvature change of the segment ensemble. Figure 9 shows the general configuration for the CELT sensors. The electronics can be a modernized version of the Keck electronics. These sensors should be much less expensive than the Keck sensors.

The active control system for the primary mirror works by taking the edge sensor height measurements and deducing the segment position errors. The system calculates a set of actuator commands required to correct any segment position errors. This operation is carried out as a matrix multiplying the vector of sensor readings to yield the vector of actuator commands. Chanan et al (2000), MacMartin and Chanan (2002) have analyzed the noise propagation of this system and found that in spite of the great increase in number of sense and control elements, the noise propagation is only slightly worse than Keck, and far from being a problem.

4 STRUCTURE

As summarized above, a conceptual design for the telescope structure has been developed by Medwadowski (Medwadowski, 2002). The structure is shown in Figures 3-5. Although the design is by no means complete, its purpose was to develop potential solutions to key problems and to uncover other problems that might be missed without a detailed analysis.

The support of the secondary mirror poses interesting structural problems. On one hand the stiffness of the primary-secondary connection is very important for optical alignment. On the other hand, one wants to minimize the optical blockage of the incident light by the structure and minimize the cross section of the structure to wind. The design indicated in Figures 3-5 is a preloaded structure with tension and compression members. It has a blockage of the primary that is about 1%, and the wind cross section is less than that of the Keck telescope structures. The structure is extremely stiff, and if taken by itself (on a solid footing) would have a natural frequency of about 10Hz.

The segment support has been considered and has led to the idea that segments will be pre-assembled into clusters (of 19 segments) and that 60 clusters will attach to the mirror cell structure (Figure 10). Each cluster will attach at three points and allow simple attachment and removal of a cluster.

To improve the stiffness of the primary mirror support, we have chosen to support the primary rather directly from the back, with large cradles. This leads to a number of difficulties. Due to the relatively fast primary (f/1.5) the center of gravity wants to be relatively near the primary. However, we prefer the tertiary mirror above the primary to allow it to feed multiple instruments on the Nasmyth platforms. The cradles are optimally located to minimize the deflections of the primary. They are large in order to support the entire primary, and their centers lie along the elevation axis/center of gravity. However, they cannot be made into complete circles without blocking the primary. These large cradle structures transfer their load onto 4 hydrostatic pads on the yoke. This means that the 4 load transfer points may be located anywhere along the cradles depending on the zenith angle. This in turn suggests that the entire cradle needs to be extremely stiff in order to transfer loads anywhere along its length. This will lead to a very massive cradle, which will shift the center of gravity behind the primary. At this time, these issues are not entirely resolved. The most obvious issue is that the natural frequency of the structure is only about 2Hz, with deformations of the cradle at the bearing load points being the dominant cause. A goal of the next design iteration is to significantly increase the natural frequency

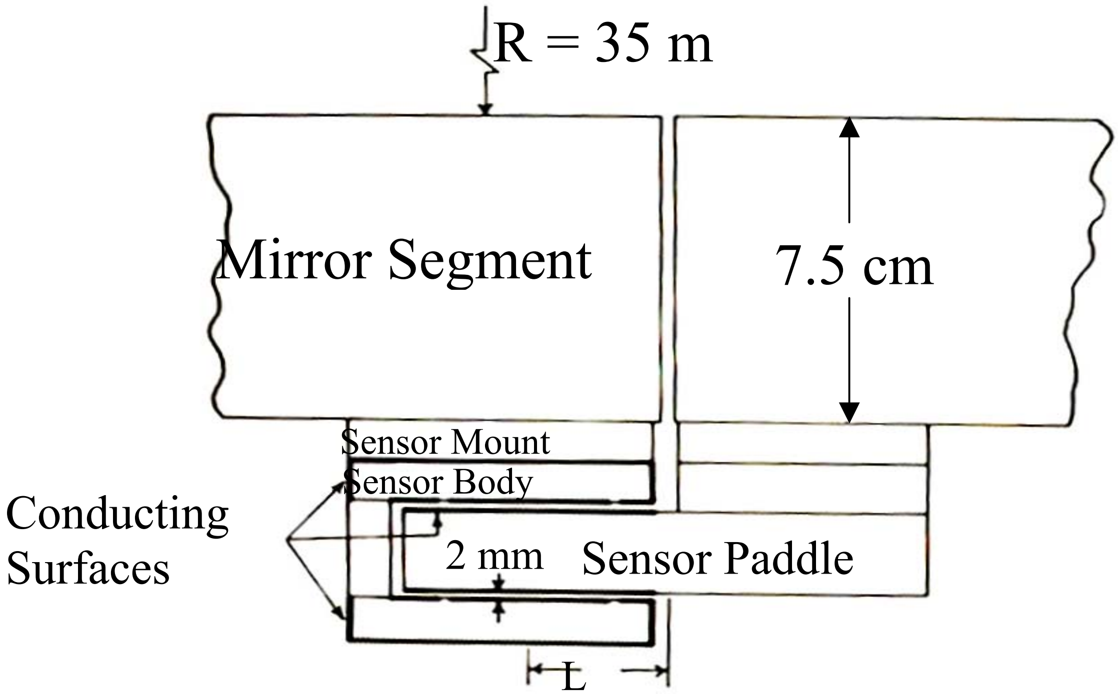

Figure 8. Keck edge sensor geometry

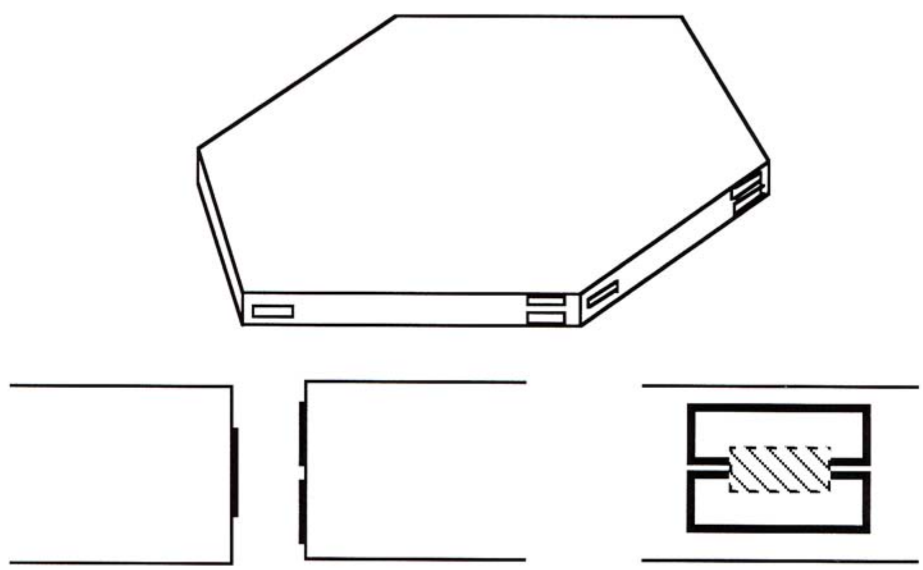

Figure 9. Proposed CELT edge sensor geometry

5 ENCLOSURE

As stated above, the enclosure needs to have an inside diameter of 84m to allow independent motion of the telescope. We assume a wall thickness of 3m will be sufficient, and thus estimate the external diameter will be 90m. At this time we do not have a detailed design for this structure, but note that although quite large, it is smaller than many movable stadium domes, and it is about the same size as a proposed observatory dome that was costed by Temcor (Mixter and Porter, 2000). The up and over shutters, with three sections will allow maximum wind shielding at all elevation angles. Other dome designs may also be satisfactory and will be explored more carefully in Phase 2. A few conceptual ideas are shown in Figure 11 (courtesy New Initiatives Office).

6 ADAPTIVE OPTICS

Perhaps the most technically challenging aspect of CELT is the adaptive optics system. Dekany et al (2002) has considered several types of AO systems with different scientific capabilities. At this time the most generally useful system appears to be a Multiconjugate System (MCAO).

In order to achieve reasonable sky coverage, we believe that laser beacons will be needed as artificial stars. Considering the size of the telescope, Sodium beacons at a height of 90km are preferred over Rayleigh beacons. Multiple laser beacons will be needed. Currently these lasers are unavailable, but several groups around the world are actively pursuing different designs for making such lasers. We are optimistic that, with some additional support from CELT, at least one of these laser beacon technologies will be available for CELT.

The MCAO system itself will require 3-4 deformable mirrors (DM) conjugate to different heights in the atmosphere (Bauman and Dekany, 2002). To achieve our goals of Strehl = 0.50 at 1μm, we will need roughly 6000 actuators in each of these deformable mirrors. Such DM's are not currently available. This many actuators may be available in the near future on MEMS type DM's, but these DM's are very small, and not suited to the large fields of view (2 arcminute) we want for CELT. Thus, DM's are a key technology for CELT, and will be actively pursued in Phase 2.

Other AO issues also confront us. The wavefront sensors will almost certainly exceed in size any currently available, and will need development. The mathematical algorithm for reconstructing the wavefront in real time is likely to be challenging, since the conventional matrix multiply approach requires computing power that will not be available even 10 years from now. The optical design of the AO system faces serious issues when it attempts to image both natural stars and sodium beacons simultaneously. Finally, the modeling tools needed to design the AO system and make sensible tradeoffs do not exist. No robust scaling laws for MCAO systems have been developed, and the simulation tools are currently too slow for this size telescope.

7 SCIENTIFIC INSTRUMENTS

We have carried out conceptual designs of representative science instruments for CELT. These include a high resolution, seeing-limited spectrograph, a fiber-fed multi-object seeing-limited spectrograph, and an AO fed integral field spectrograph. Although the instruments will be both large and challenging, science instruments for a 30-m telescope appear feasible. Taylor (2002) gives details about these instruments.

8 CONCLUSIONS

The CELT conceptual design has been completed, and a feasible design developed that allows us to better understand the problems of designing this telescope. In the next phase of work (Phase 2) we will re-examine all of our assumptions and develop a telescope design that is more finely optimized. Having found many technical challenges, we will carry out a set of design and prototyping activities in order to reduce the technical risks and also develop low cost components.

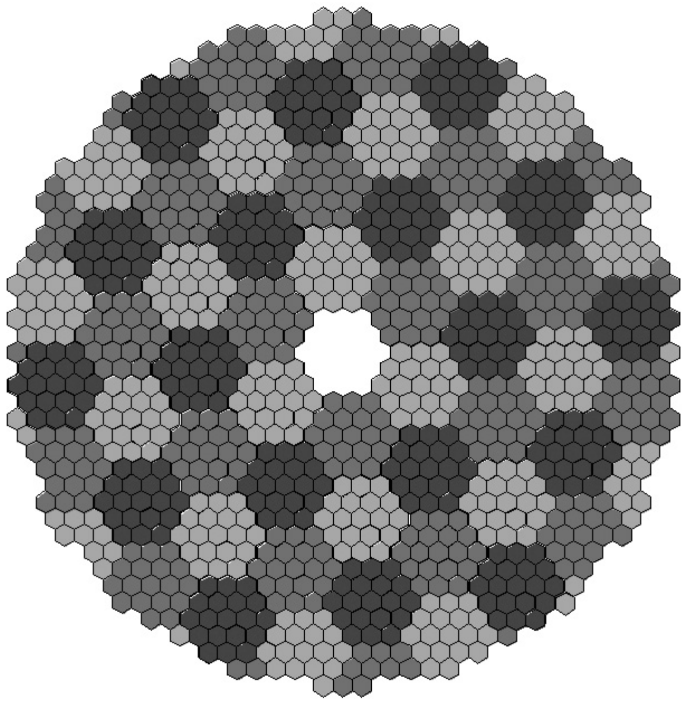

Figure 10. Cluster geometry

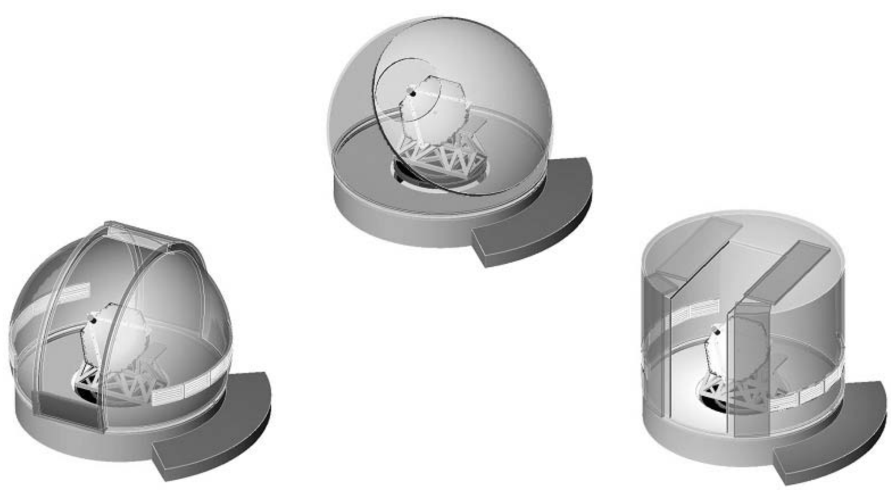

Figure 11. Enclosure design options (from NIO)

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