Design Concepts for the California Extremely Large Telescope (CELT)

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ABSTRACT

The California Extremely Large Telescope (CELT) is a study currently underway by the University of California and the California Institute of Technology, to assess the feasibility of building a 30-m ground based telescope that will push the frontiers of observational astronomy. The telescope will be fully steerable, with a large field of view, and be able to work in both a seeing-limited arena and as a diffraction-limited telescope, with adaptive optics (AO).

Keywords, Extremely large telescopes, mirror segments, optical design, sensors, actuators, mirror fabrication

1. INTRODUCTION

The University of California and California Institute of Technology (partners in Keck Observatory) are collaborating to build a 30-m telescope, designed to be fully steerable and operate on the ground. With its Ritchey-Chretien optical design, it will have a large, 20-arcminute, field of view; and with planned adaptive optics, it will produce diffraction-limited images for wavelengths as short as 1 µm. The early ideas for this telescope are described by Nelson and Mast (1999).

Such a telescope will have remarkable scientific power, with ten times the collecting area of the current world's largest telescope (Keck) and with adaptive optics, angular resolution of 0.007 arc seconds at 1 µm. With such capabilities, CELT will be able to probe into star and planet forming regions with sub-AU resolution, and probe the high-z universe with unprecedented resolution and sensitivity.

Caltech astronomers (J. Cohen, G. Djorgovski, R. Dekany, R. Ellis, S. Kulkarni, W. Sargent, C. Steidel) and UC astronomers (M. Bolte, G. Chanan, A. Ghez, J. Graham, J. Larkin, T. Mast, I. Mclean, J. Miller, J. Nelson, D. Tytler, S. Vogt) are studying various aspects of the capabilities and design of CELT, including the scientific justification, instrument design, telescope design, enclosure design, site selection, etc.

2. GOALS OF CELT

The broad scientific requirements call for a general purpose telescope to accommodate a variety of scientific uses. It will operate in a seeing-limited mode from 0.3 µm to 30 µm with a 20-arcminute field of view. In addition, diffraction-limited imaging with AO will be available down to wavelengths as short as 1 µm. We have as a goal that a Strehl ratio of 0.5 at 1 µm should be commonly available. This requires that, with the use of adaptive optics, the residual rms wavefront error should be under 133 nm. In the AO mode, we also hope to achieve 1-2 arc minute fields of view at short wavelengths. This will require multi-conjugate AO and likely require the use of multiple laser beacons to eliminate cone effect and achieve coverage over a large fraction of the sky.

3. SCIENTIFIC JUSTIFICATION FOR CELT

For such a general-purpose telescope, it is expected that there will be a myriad of important scientific applications, most of them to be discovered in the using of CELT. This is a typical discovery model for giant telescopes that has been proven for generations.

It is our desire that CELT be built in the next 10-15 years. This will make it contemporaneous with NGST, an 8-m cold space telescope that will be particularly effective in the thermal infrared wavelengths. In some wavelength regions (> 2 µm), the much lower background radiation that NGST will likely experience makes it significantly more sensitive for point source imaging than CELT, even though CELT will have 14 times the collecting area. However, CELT will have over 3 times better angular resolution at any wavelength, and for many areas of spectroscopy the much greater collecting area will allow CELT to study objects spectroscopically that NGST can only image. Thus, we expect that these two facilities will be complementary in many ways, and their simultaneous existence should be a significant benefit for both instruments.

Seeing-limited observations will consist of high-resolution spectroscopy in the visible and near infrared, particularly of extremely faint or high redshift objects. In addition, we expect there is an important role for multi-object spectroscopy of faint objects. Thus, when adaptive optics is not applicable, and when the objects under study are extended (such as galaxies) we expect seeing-limited observations will be extremely powerful.

Diffraction-limited observations will run the gamut from imaging to spectroscopy and over wavelength ranges from 1–25 µm. High z objects will radiate largely in the near infrared and measuring the spatial and spectroscopic structure of these distant objects is an ideal application for CELT. Such studies have the potential for disentangling the confusion surrounding the early formation and development of galaxies.

Within our own galaxy, AO observations with CELT can help in the study of star formation and in the study of planetary disk formation. Again, the combination of diffraction-limited angular resolution to directly resolve the structure of these objects (under 1 AU at 100 pc) and spectroscopy at the same angular scale should greatly enhance our knowledge of how these star and planet forming regions develop.

4. BASELINE DESIGN OF CELT

4.1 Performance goals

CELT is to be both for seeing-limited and diffraction-limited observations. In the seeing-limited regime, it should produce an image quality limited by the atmosphere, not the telescope optics. Thus we require that the telescope produce 0.25 arc second images (FWHM). We also require that the telescope provide this image quality over 20 arc minutes, to allow for multi-object work. CELT must support a variety of potentially large instruments, so we expect large Nasmyth platforms will be available. Sky coverage should be large, so we require a telescope that is fully steerable and can work within 25° of the horizon.

The infrared performance be un-compromised in the near infrared and provide good performance in the thermal IR. Of great interest is the near IR performance with adaptive optics. We have set as a goal that the telescope AO system should deliver diffraction-limited images down to 1.0 µm with Strehl's of 0.5. The technology for this does not yet exist, but a variety of efforts in AO are encouraging that this objective will be reachable in 10-15 years. Thermal IR performance is also important, but with the expectation that NGST will provide much greater sensitivity, we are not insisting that thermal IR adaptive optics systems be pushed to the limit of lowest emissivity.

4.2 Optical configuration

The optical design for CELT is a Ritchey-Chretien two mirror system. This rather naturally provides a large, 20 arc minute field of view with under 0.5 arc second images (100% enclosed energy). This focus is free of coma and only suffers from astigmatism, which grows quadratically with field angle. The primary will be 30 m in diameter, and for compactness, the primary f- ratio will be f/1.5. The final focus will be f/15, delivering a final focus with about 2 mm/ arc second as its plate scale. Such a giant telescope produces very large seeing-limited images, a challenge for the design of seeing-limited scientific instruments. The 20 arc minute field is 2.6 m in diameter. The basic optical parameters are shown in Table 1, along with those of Keck Observatory for comparison.

Since such a telescope will be rather expensive, we are attempting to simplify the design in order to minimize the cost. Thus, we expect that there will be no prime focus, nor a Cassegrain focus. We expect that all scientific work will be done at the bent Cassegrain and Nasmyth foci.

The f-ratio of the primary and the final f-ratio are clearly very important parameters in determining the cost and performance of the telescope. Although we have a baseline for these, we are still exploring whether these are optimal. The field of view of the telescope, with images containing 100% of the light in 0.5 arc seconds is shown for various primary and final f-ratios in Table 2. As one can see, over this range, the field of view is not strongly influenced by either parameter. The secondary mirror diameter that provides these primary and final f-ratios is given in Table 3. We have assumed no oversizing for the secondary, and assume a back focal distance of 15 m. Here changing the parameters has a more evident influence, and one must assess the expense and difficulty of making large secondaries to aid in this decision.

Table 1: Baseline Telescope Optical Design Parameters

	CELT	Keck
primary diameter (m)	30	10
primary focal ratio	1.50	1.75
backfocal distance (m)	15.0	2.5
primary radius of curvature k (m)	90	35
primary conic constant K	–1.0028	-1.003683
secondary radius of curvature (m)	–12.12	–4.738
secondary conic constant	–1.525	–1.644
final focal length (m)	450	150
field of view diameter (arc min)	20	20
secondary diameter (m)	3.6	1.4

Table 2: Field of view (arc minutes) with 100% enclosed energy as a function of primary and final f-ratio

primary		**Final f-ratio**	
f-ratio	**10.0**	**12.5**	**15.0**
1.0	18.1	18.2	18.2
1.1	18.6	18.7	18.8
1.2	19.1	19.3	19.3
1.3	19.7	19.8	19.9
1.4	20.1	20.3	20.4
1.5	20.6	20.8	20.9

Table 3: Secondary mirror diameter (m) as a function of primary and final f-ratio

primary		**Final f-ratio**	
f-ratio	**10**	**12.5**	**15**
1.0	4.09	3.33	2.81
1.1	4.32	3.53	2.98
1.2	4.55	3.72	3.15
1.3	4.78	3.91	3.31
1.4	5.00	4.10	3.48
1.5	5.22	4.29	3.64

4.3 Primary Mirror

The primary mirror will inevitably be segmented. The layout of the segmented primary, and comparison with the Keck primary is shown in Figure 1. A key parameter for this design is the size of the segments. For a variety of reasons, hexagonal segments are best suited for this telescope. The radius or edge length is expected to be 0.5 m. This is significantly smaller than the 0.9 m edge length of the Keck segments. There are several benefits from a reduced segment size. The primary is closer to circular, which simplifies some parts of scientific instrument design. The small segments can be relatively thin, thus reducing mirror material cost, mirror mass, (and thus telescope mass) and thermal mass. The smaller segments will be easier to handle throughout the manufacturing and assembly processes. The alignment tolerances for smaller segments are relaxed, thus easing assembly and relaxing requirements for thermal and gravitational deflections. Finally, segment fabrication will be simpler, due to the reduced asphericity of individual segments. We now discuss these issues in more detail

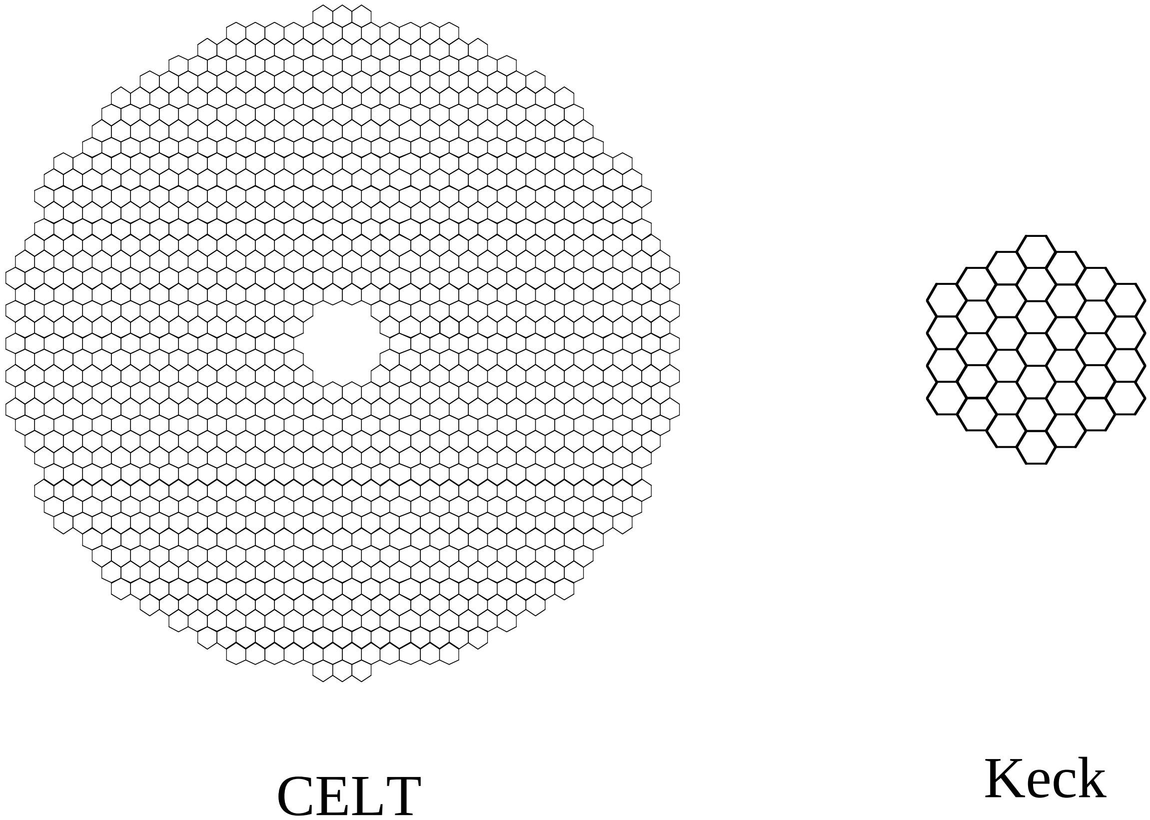

Figure 1: Primary mirror layout for CELT (1080 segments) and Keck (36 segments)

Our experience with the manufacture and support of the Keck segments and various issues related to the active control suggests to us that smaller segments will be more cost effective. This conclusion is by no means simple or obvious, and more detailed studies must be carried out before this choice is made final. A basic relationship is that gravity deformations of segments are given by

$$\delta = c\frac{a^4}{n^2h^2}$$

Where δ is the gravity driven deformation, a is the segment radius, n is the number of axial support points, and h is the segment thickness. This simple relationship shows the great value of reducing the segment size. For a given deformation, smaller a can lead to both a thinner mirror (less mass, less thermal inertia, less cost) and a simpler axial support (fewer support points and looser tolerances on the axial support).

On the other hand, smaller segments implies more segments, more edge sensors, more actuators, and worse error propagation for the segment active control system. Below we will discuss these issues and highlight where we need more information in order to make an informed tradeoff between these conflicting needs.

4.4 Segment Fabrication

Segment fabrication is a central issue for CELT. Polishing the Keck segments was the most important and difficult aspect of building the Keck telescopes, and we expect this to be true for CELT as well. The segments must have extremely high optical quality, and be the correct section of the master primary-mirror surface. This implies optical tests must have an unusual absolute accuracy. In addition, the segments are not individual figures of revolution about their mechanical centers, thus traditional polishing methods are not applicable.

The details of our suggested approach to segment fabrication are described by Mast, Nelson and Sommargren (2000) and will only be summarized here. The degree of asphericity of the segment (the amount a segment surface differs from a sphere) is likely to be a key driver on the cost of segment fabrication. For the range of segments anticipated for CELT, one can represent almost the entire asphericity of the segments by astigmatism. Using Zernike polynomials to represent this, we can write the Zernike coefficient representing the amount of astigmatism as

$$C_{22} = \frac{Ka^2 R^2}{4k^3}$$

Where K is the conic constant of the primary, a is the segment radius, R is the segment off axis distance, and k is the primary mirror radius of curvature. For the optical design given in Table 1, the outermost segment has $C_{22} = -19$ µm. The most aspheric Keck segment has $C_{22} = -100$ µm, or about 5 times larger the CELT. Thus we expect CELT segments will be significantly easier to polish.

Using anything approaching traditional optical fabrication techniques, flats and spherical surfaces are the simplest and least expensive optical surfaces to produce. Our suggested technique is to use a variant of Stressed Mirror Polishing, the technique used to polish the Keck segments (Lubliner and Nelson, 1980; Nelson et al., 1980). For the application of CELT, where many segments are needed, the variant we suggest is to use planetary polishing techniques to spherically polish several mirrors simultaneously, and on each mirror to use a stressing fixture to elastically deform the desired non-spherical optical surface into a sphere. With this approach we hope to come close to the efficiency of polishing spheres.

Segment fabrication procedures can be summarized by the following steps.

1. Grind and polish back surface of circular blank to a spherical shape
2. Apply stressing fixture to edge of circular mirror
3. Apply suitable forces to perimeter of mirror to elastically deform it as planned
4. Grind and polish front surface of mirror on planetary polisher
5. Remove applied forces and test surface. If sufficiently close to desired surface cut hexagonal segment out of circular mirror. The mirror is expected to warp to some extent at this point, probably a modest fraction of a micron. Thus polishing accuracy need not be better than this.
6. Install segment on final support system
7. Carefully test hexagonal segment surface
8. Ion figure segment to remove any residual errors (polishing errors, warping, support errors, positioning errors)

4.5 Active Control

The ensemble of 1080 segments needs to be assembled and held in the correct position in order that the optical system work properly. The segment piston and tip-tilt errors need to be controlled to the 10 nm level. Since both gravitational and thermal effects on the support structure (the 30-m diameter mirror cell) will be many orders of magnitude larger than this allowed error, some type of active control of the segments will be necessary. There are two basic aspects of this problem.

First, the segments need controlled to a stable configuration. As with Keck, we plan to use segment edge sensing as the basic technique. Displacement sensors capable of measuring changes in the height difference between adjacent segments will be used. Keck used two sensors on every inter-segment edge, and we plan the same geometry here.

Second, the segments need to be accurately positioned to their desired locations. We will carry out this calibration using starlight and an alignment camera. With the segment positioned stabilized, once properly aligned, they will stay aligned. This procedure is used on the Keck active control system and works well.

The basic principle is that edge sensors will be measured (at roughly 5 Hz) and then with a matrix multiplication of the sensor vector, by a fixed control matrix (defined only by the segment array geometry), the desired actuator moves will be calculated. These moves will then be sent to the actuators, thus restoring the segments to their desired location.

Since CELT has many more segments than Keck, an important issue is the effect of sensor noise propagation. Mathematical modeling of random sensor noise propagation into segment position errors (or actuator position errors) has been carried out by Chanan et al (2000). This analysis shows that the rms surface error of the primary mirror grows roughly as the square root of the number of segments, times the sensor noise. The resulting surface errors are extremely smooth, and the largest part of the error is in very low spatial frequency errors.

One subtlety of this system is that the CELT proposed sensors are on the segment edges, whereas the Keck sensors were offset from the inter-segment edge. This difference means that a single mode of deformation is undetectable with CELT. This mode corresponds to every adjacent segment pair tilting by the same dihedral angle. This spherically symmetric mode (called focus mode at Keck) is completely unsensed with CELT and thus uncontrollable. To eliminate this problem we plan to use a low order wavefront sensor with CELT, much along the lines of modern guiders used on 8-m telescopes. With such a low bandwidth wavefront sensor, both this unsensed mode, and the lowest order modes of the primary can be adequately controlled in CELT. Such a wavefront sensor will be used in conjunction with the edge sensors, with both sensor signals being combined into a single control system for the primary mirror.

Chanan's analysis shows that edge sensor noise at the level of the Keck sensing system is adequate for CELT. In addition, Chanan has shown that the slope errors on the segments (useful for a geometric optics analysis of the system) are almost independent of the number of segments, and depends mainly on the ratio of the sensor noise to the segment size. Again, the quantitative values found by Chanan suggest that sensors as good as the Keck sensors will be adequate for CELT.

4.6 Sensors and Actuators

With Keck, the edge sensors were built to provide differential capacitive sensing of segment height differences. These sensors are composed of Zerodur plates. On Keck we attached the sensors to the backs of the segments and they were extended across the gap to the back of the neighboring segment. This was mechanically complex and rather expensive. For CELT we plan to greatly simply the mechanical design of the sensors, by using capacitor plates attached to the faces of the edges of the segments. Such a design should virtually eliminate the expensive and precise mechanical parts used for Keck. The electronics can be rather similar. The details of this sensor design are given by Mast et al (2000)

For the 1080 segments we will need 3240 actuators. Preliminary structural designs suggest that it will be possible to provide a sufficiently stiff mirror cell so the needed actuator range will be about 1mm. This is comparable to the range requirements for the Keck actuators. Thus we could use Keck style actuators on CELT and achieve adequate performance. However, the Keck actuators are expensive, so we expect to develop or acquire a significantly less expensive actuator. The CELT segments are much lighter than those for Keck, so some of the requirements will be easier to meet. A more detailed discussion of the actuator requirements and plans are given by Mast and Nelson (2000).

5. KEY ISSUES FOR CELT

The work on CELT is still quite preliminary. At this early stage there are many unknowns and a number of detailed tradeoffs that must be carried out in order to achieve a cost-effective design that meets the major scientific requirements. We are currently undertaking various design studies to resolve these major issues to develop a sound conceptual design. Some of the major outstanding issues are briefly described below.

5.1 Science instruments

For a 30-m telescope, scientific instruments will be a major concern. Simply scaling up seeing-limited instruments from 8-10 m telescopes will not in general be practical or efficient. Some optical elements cannot be scaled due to material limitations, and other components such as the photon detectors, cannot be scaled. Thus is it important that preliminary designs of candidate scientific instruments be carried out. This is meant to establish feasibility, and also to determine if changing the telescope parameters will have a significant impact on the instrument design.

We also plan that this telescope deliver diffraction-limited images down to 1 μm with use of adaptive optics. Thus it is important that we also generate preliminary designs of diffraction-limited scientific instruments to ensure they are feasible and to establish to what degree the telescope parameters will significantly impact the instrument design.

Some of the members of the CELT team are actively pursuing these instrument designs. Basic parameters such as likely mechanical dimensions, weight, and field of view will be central objectives of these studies.

5.2 Adaptive optics

It is important that CELT be able to operate at the diffraction limit down to 1 μm. At this time the technology required for the adaptive optics system is not available. Thus we must ensure that the telescope will be capable of supporting the AO system when it becomes available, without knowing fully the details of the AO system. The AO system will significantly drive the optical requirements of the segments and their control. A particularly delicate issue is how the design of the AO system might be influenced by the optical design of CELT. In particular, the choice of the final f-ratio and the choice of secondary mirror, may have significant impact on the AO system.

We expect that an AO system capable of providing Strehl ratios of 0.5 at 1 µm will require a deformable mirror with roughly 5000 actuators, and a correspondingly sophisticated wavefront sensing system. Components for these do not exist today. Dekany etal (2000) have made a preliminary assessment of the various kinds of AO systems that might be useful for CELT. It is our plan to carry out preliminary optical designs for these candidate AO systems so we can understand their likely performance and the degree in which they are coupled to the telescope optical design.

Since the technology is not currently available (sensors, deformable mirrors, multiple laser systems) it is important to assess the current technology and find where the technology is likely to evolve. We plan to help support key aspects of this technology to ensure it is available for the early years of use of CELT.

5.3 Telescope geometry

The geometry of the telescope structure still needsto be defined. We need to resolve basic issues such as the location of the elevation axis relative to the primary mirror. Optical telescopes traditionally have the elevation axis in front of the primary mirror. Radio telescopes traditionally have the elevation axis behind the primary mirror. Where should it be for CELT? This issue may strongly impact the optical parameters, the size of the enclosure, and the size, stiffness and complexity of the telescope structure.

The design of the upper part of the telescope is also uncertain. Wind loads on the telescope are likely to be important, particularly for diffraction-limited operation. Thus it may be that designs that reduce the wind cross section near the top of the telescope are strongly favored. Secondary support systems such as tripods or quadrupods (such as one typically sees on radio telescopes) might be favored over more traditional optical telescope top ends that have top end rings and tensioned spiders supporting the secondary.

When we have a clearer sense of the space requirements for the instruments we can sensibly lay out the Nasmyth platform requirements and the bent Cassegrain requirements.

5.4 Primary and Final f-ratios

The primary-mirror focal length will determine many aspects of the CELT design. A longer focal length, will require a larger enclosure. The focal length may also strongly influence the telescope geometry and the design of the telescope top end since it may influence the effect of wind loads on the telescope performance. The asphericity of the segments varies as the inverse cube of the focal length, so segment fabrication is more difficult for a smaller focal lengths. The alignment tolerances of the segments varies as the square of the segment size and the inverse cube of the focal length. Thus, the segment size and the primary focal length may be strongly coupled.

The final focal ratio will also be influenced by the primary focal length. The final f-ratio will depend directly on the size of the secondary and the primary mirror focal length. Larger convex secondaries may be extremely expensive and may increase the cross section for wind loading on the telescope. The final f-ratio may have a significant impact on the capabilities of the seeing-limited and diffraction-limited science instruments.

We have established preliminary values for the primary focal length (45 m) and the final f-ratio (f/15). However, as the above discussion reveals, these parameters are deeply coupled to many characteristics of the telescope that could strongly influence both cost and performance. Thus the final selection of these parameters must be done with care. The studies we are carrying out will help us to intelligently determine suitable values for these parameters.

5.5 Primary mirror segment fabrication

Segment fabrication is likely to be a critical driver of the cost of CELT. The optical requirements are extremely tight, driven by AO. Segments for CELT will have optical requirements typically twice as tight as Keck. As we have seen segment size and primary mirror focal length directly influence the asphericity of the segments. Although we know this is important, only by working with potential segment manufacturers and understanding better the fabrications issues driving cost, will we be able to sensibly determine these parameters and find a cost effective fabrication technique.

5.6 Secondary mirror

The size of the secondary mirror is likely to be a strong cost driver. As indicated above, secondary size directly influences final f-ratio, which may be closely coupled to science instrument complexity. Secondary size may influence wind disturbances to the telescope. Further, AO may benefit from adaptive secondary mirrors, particularly in the thermal infrared. Such adaptive secondary mirrors may have severe size constraints, which clearly influences the optical design. The conflicting traits of an adaptive secondary may drive us to allow for multiple secondary mirrors. Allowing for rapid changes between observing configurations, particularly to allow for changing weather and seeing conditions, may require us to find some rapid means of changing secondary mirrors.

5.7 Enclosure

It is our judgement that an enclosure is needed for CELT, both for weather protection and for wind shielding during observations. Although such a structure is surely practical, it will be expensive, and its size will be driven by the primary focal length and the position of the elevation axis. Mixter (2000) has suggested a design for a 90-m diameter dome that might be suitable for CELT.

6. CONCLUSIONS

The basic design for CELT appears robust. The key issues relate to finding the most cost-effective strategy for CELT, not conceptual questions about whether such a telescope can be built and work effectively. Currently there are many open issues in the design of CELT and many problems need to be understood simultaneously in order to intelligently develop the design and freeze key parameters. Work on these details and tradeoffs is underway. This period of design is exciting and invigorating, and we look forward to working on these key issues, both within our study group and with the greater community.

7. ACKNOWLEDGMENTS

I would like to thank Terry Mast and Gary Chanan for many valuable discussions leading towards the ideas presented in this paper

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