CELT Report No. 12
Design Team Quarterly Report 1 December 2000

Contents

1. Introduction

The University of California and the California Institute of Technology (partners in the W. M. Keck Observatory) are collaborating to build a 30-meter telescope (CELT), 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 micron.

The plan for a year-long Conceptual Design Phase is described in CELT Report No. 9 "California Extremely Large Telescope (CELT) Conceptual Design Plan", Jerry Nelson, Terry Mast, Gary Chanan, Richard Dekany (July 2000). This report is the first quarterly report describing the progress of this Conceptual Design Phase.

Table 1 lists some aspects of the full CELT Observatory Project and organizes the thirty conceptual design phase tasks by aspect.

Table 1. Tasks in context of full CELT program

Observatory Requirements	**Task [1]**
Telescope Design	
Error Budgets	**Task [2]**
External Design Driver: Wind	**Task [3]**
Optical Design	**Task [4]**
Primary Mirror	**Tasks[5 -17]**
Auxiliary Optics	**Tasks[18-19]**
Telescope Structure	**Tasks[20-21]**
Adaptive Optics	
Modes of operation	**Task [22]**
Error budgets	**Task [23]**
Alternative Design Concepts	**Tasks[24]**
Conceptual Design Review	**Task [25]**
Preliminary Design Plan	**Task [26]**
CELT Working Groups	**Task [27]**
Conceptual Design Phase Management	**Task [28]**
CELT Website Management	**Task [29]**
Contingency Management	**Task [30]**

Table 2 gives the titles of the 30 conceptual design-phase tasks and serves as a table of contents.

Table 2. Task List

2. Summary

This first quarter of the CELT conceptual design phase has been a productive start given the necessary limitations of project-start overhead activities.

We have hired consultants to work with us on the telescope structure, the segment support actuators, and the segment passive support system. A study of an attractive method for interferometric testing of the segment has proceeded at, and is funded by, the Lawrence Livermore National Laboratory. Significant design work has occurred at UCSC, JPL, and UCI.

Reports and Technical Notes series were started to document the design efforts, and a website provides access to these as well as information about CELT personnel and calendar activities.

Significant progress was made this quarter on the issues listed below.
Details are given in the Section 6.

telescope structure

stressing fixture for segment fabrication
interferometric testing of segments
segment passive support
segment support actuators

spatial frequency response of the primary mirror control
algorithms to combine displacement and wavefront sensor reading
camera for the desired sensor readings

adaptive optics mode definitions
adaptive optics optical designs

These efforts will continue into the second quarter. Other issues that we will begin to address with significant effort in the second quarter include

observatory requirements
error budgets
segment displacement sensors
bearings, drives, encoders
algorithms for primary, secondary, & guiding control

3. Budget

DESCRIPTION	budget	jul	aug	sep	oct	nov	liens	total spent	balance
ADMINISTRATION									
Project Management	20			4				4	
Travel	20		6			3		9	
Website Management	10								
Conceptual Design Review	15								
TOTAL ADMIN	**65**	**0**	**6**	**4**	**0**	**3**	**0**	**13**	**52**
OPTICS									
Optical Design	5								
Segmentation Geometry	5								
Segment Material	5								
Segment Fab vendor candidates	20								
Stress fixture design, fab & test	45								
Design segment passive support	40					16	40	56	
Combine Displace Sens/TCWS	12								
Primary mirror control SFR	19								
Segment Displacement Sensors	60								
TCSE hardware Design	7								
Segment Support actuators	45					8	37	45	
Alignment Camera Design	14								
TOTAL OPTICS	**277**	**0**	**0**	**0**	**0**	**24**	**77**	**101**	**176**
ADAPTIVE OPTICS									
Conceptual AO optical designs	50								
TOTAL AO	**50**								**50**
TELESCOPE									
Wind influence on telescope	60								
Telescope Structure Design	65				25	10	30	65	
Prelim design bearings, drives, encoders	25								
TOTAL TELESCOPE	**150**	**0**	**0**	**0**	**25**	**10**	**30**	**65**	**85**
WORKING GROUPS	**50**								**50**
Science									
Adaptive Optics									
Enclosure /support Facilities									
Telescope									
Site									
Instruments									
CONTINGENCY	**158**								**158**
TOTAL	**750**	**0**	**6**	**4**	**25**	**37**	**107**	**179**	**571**

4. Schedule

Activity	duration	start	end	% done
[1] Observatory Requirements	255d	9/22/00	9/24/01	0%
Observatory Requirements Document	51w	9/22/00	9/24/01	0%
Quarterly Review #1	0d	12/1/00	12/1/00	0%
Quarterly Review #2	0d	3/6/01	3/6/01	0%
Quarterly Review #3	0d	6/5/01	6/5/01	0%
Quarterly Review #4	0d	9/11/01	9/11/01	0%
[2] Error budgets	255d	9/22/00	9/24/01	15%
Adaptive Optics on	51w	9/22/00	9/24/01	15%
Adaptive Optics off	51w	9/22/00	9/24/01	15%
Internal Review	0d	1/15/01	1/15/01	0%
Detailed Review	0d	2/1/01	2/1/01	0%
[3] Analyze and model wind influence on telescope	125d	9/22/00	3/26/01	10%
Characterize Free Winds at Sites	25w	9/22/00	3/26/01	10%
Determine Wind Force on Dome	25w	9/22/00	3/26/01	10%
Determine Wind Spectra Inside Dome	25w	9/22/00	3/26/01	10%
Determine Wind Dynamics on Primary Mirror	25w	9/22/00	3/26/01	10%
[4] Complete the optical design	255d	9/22/00	9/24/01	26%
Optical Design	51w	9/22/00	9/24/01	25%
Initial Optical Design	1d	9/22/00	9/22/00	100%
Revised Optical Design	1d	2/2/01	2/2/01	100%
Conceptual Stage Optical Design	0d	9/11/01	9/11/01	0%
[5] Establish the segmentation geometry	51w	9/22/00	9/24/01	25%
[6] Establish the segment material	51w	9/22/00	9/24/01	25%
[7] Establish the segment fabrication vendor candidates	51w	9/22/00	9/24/01	25%
[8] Establish the segment fabrication cost	51w	9/22/00	9/24/01	25%
[9] Stressing fixture design, fabricate, and test"	127d	9/22/00	3/28/01	27%
Calculate Conceptual Design & Reqiurements	14w	9/22/00	1/8/01	50%
Design Stress Fixture	4w	1/4/01	1/31/01	0%
Fabricate Stress Fixture	4w	2/1/01	2/28/01	0%
Test Mirror Stress Fixture	4w	3/1/01	3/28/01	0%
[10] Define the segment fabrication figure tests	255d	9/22/00	9/24/01	22%
Design an LVDT system	4w	1/4/01	1/31/01	0%
Test LVDT System	4w	2/1/01	2/28/01	0%
Develop Optical Test of Segment Figure	51w	9/22/00	9/24/01	25%
[11] Design the segment passive support	206d	9/22/00	7/17/01	23%
write requirements	206d	9/22/00	7/17/01	23%
write contract and award	2w	9/22/00	10/5/00	100%
segment support study	15.2w	10/6/00	1/30/01	50%
Freeze Concept	0d	1/4/01	1/4/01	0%
Fabricate Prototype	8w	1/31/01	3/27/01	0%
Test Protype	16w	3/28/01	7/17/01	0%
[12] Algorithms to combine Displacement & TCWS readings	51w	9/22/00	9/24/01	25%
[13] Study spatial frequency response of the primary mirror control	51w	9/22/00	9/24/01	25%
[14] Segment displacement sensors (design, fabricate, test)"	159d	1/3/01	8/13/01	0%
write requirements	2w	1/3/01	1/16/01	0%
write contract	4.25w	1/17/01	2/15/01	0%
Segment displacement sensor study	25w	2/20/01	8/13/01	0%
[15] Design Telescope-Control Wavefront Sensor (TCWS) hardware	51w	9/22/00	9/24/01	15%

[16] Segment support actuators (design, select, test)"	220d	9/22/00	8/6/01	13%
write requirements	220d	9/22/00	8/6/01	13%
write contract and award	2w	9/22/00	10/5/00	100%
actuator study	18w	10/6/00	2/19/01	40%
Lorell Study- Write contract and award	4w	9/22/00	10/19/00	0%
Lorell Actuator Study	16w	10/20/00	2/19/01	0%
acquire Test Acturators	8w	2/20/01	4/16/01	0%
Develop Actuator Test Program	6w	2/20/01	4/2/01	0%
Test Actuators	16w	4/17/01	8/6/01	0%
[17] Design camera required to determine desired sensor readings	51w	9/22/00	9/24/01	250%
[18] Define secondary & tertiary physical & performance parameters	51w	9/21/00	9/21/01	10%
[19] TCWS control of primary, secondary, & guiding"	25w	3/1/01	8/22/01	0%
[20] Design the telescope structure	101d	9/22/00	2/20/01	68%
Write requirements and contract goals for SJM and award contract	2w	9/22/00	10/5/00	100%
Telescope structure study	18.4w	10/5/00	2/20/01	65%
[21] Generate strawman designs of the bearings, drives, encoders"	145d	12/4/00	7/3/01	0%
Write Contract and Award	4w	12/4/00	1/9/01	0%
"Phase 1 Bearings, Drives, and Encoders Study"	16w	1/10/01	5/1/01	0%
"Phase 2 Bearings, Drives, and Encoders Study"	9w	5/2/01	7/3/01	0%
[22] Identify the candidate AO modes & define requirements for each	51w	9/22/00	9/24/01	25%
[23] Develop first order error budgets for AO components	51w	9/22/00	9/24/01	25%
[24] Develop conceptual AO system optical designs for each AO mode	51w	9/22/00	9/24/01	0%
[25] Prepare for Conceptual Design Review	5w	8/15/01	9/18/01	0%
[26] Write the Preliminary Design development plan	5w	8/15/01	9/18/01	0%
[27] Support the CELT Working Groups	51w	9/22/00	9/24/01	0%
[28] Manage the Conceptual Design phase program	255d	9/22/00	9/24/01	25%
Weekly Telecons and Team Meetings	51w	9/22/00	9/24/01	25%
CELT Workshop Meeting	0d	2/2/01	2/2/01	0%
[29] Manage the CELT Website	51w	9/22/00	9/24/01	25%

A Gantt chart will be presented at the CELT Steering Committee meeting.

5. Concerns

Although there has been important and significant progress, there are key issues that are unresolved and are required for many other parts of the study. Their timely resolution is critical.

The effects of the wind are not yet adequately understood and the plan for completing this task are vague. The effect of wind **may** be a critical driver for the telescope, but this must be quantitative. Hence completion of the telescope structural design is seriously hindered by the poor progress on understanding wind.

It **may** be that the most acceptable telescope structures (acceptable due to wind) produce significant blockage of the primary. The likely scientific impact of this blockage needs to be carefully assessed. If it is viewed as a serious problem and none of the current telescope structure designs is acceptable, then more radical departures in design may be necessary. This could drive the entire design study.

Plausible costs for edge sensors, actuators, segment support, and segment fabrication are needed before we can reasonably optimize the segment size and the primary mirror focal length. We will also need the segment alignment error budget and secure knowledge about the mirror cell gravity deformations. Concerted effort needs to be applied here so we can freeze the optical design sooner, rather than later.

Adaptive optics requires technologies not yet available and building designs around non-existent technology is risky. An adaptive secondary may be extremely challenging, so its value must be carefully understood. If needed, it will influence the telescope structure design. Further, the optical design for MCAO may drive the telescope optical design. The auxiliary requirements of MCAO (number, launch locations, power of lasers) may have a strong influence on the observatory design, and the requirements are unknown.

Many tasks are either not started or barely begun, and our ability to complete the conceptual design study in 12 months is untested. The fact that many tasks are strongly inter-related and that some key ones are barely begun is a clear cause for concern about keeping to our schedule.

6. Task Descriptions

For each task we briefly repeat from CELT Report No. 9 "California Extremely Large Telescope (CELT) Conceptual Design Plan", the description of the task. Then for each task we describe the progress made this quarter and the plans for the future.

Task [1] Determine Observatory Requirements

Description

We will write the observatory requirements which will form the over riding document that dictates the design objectives. This will evolve with discussions with the working groups and with the Steering Committee

Inputs

Working Group Reports

Impact on Other Tasks

Fundamental requirements for all tasks

Status

An early draft has been generated but not yet distributed.

Progress this Quarter

No specific progress has been made.

Plan for Future

We will issue a first draft for review by the CELT Steering Committee during December 2000.

Task [2] Error budgets

Description

Error budgets for image quality will be completed. These are being constructed for both observing modes; AO-on (in terms of rms wavefront error) and AO-off (in terms of 80% enclosed energy diameters).

Objectives

Construct global telescope error budgets and detailed error budgets for the segmented primary mirror. Also construct error budgets for image motion.

Inputs

Complete Task 4

Initial work on Tasks 5 and 10

Initial values of telescope optical design. Baseline design for primary mirror active control.

Site environmental properties

Impact on Other Tasks

All other tasks will interact strongly with the error budgets. Candidate designs will define the budgeting and the budgeted errors will drive the designs.

Status

Progress this Quarter

Initial draft error budgets for AO-on and AO-off modes have been written and are currently being refined with detailed calculations of a variety of terms. The AO-off budget is written in terms of the geometrical image size, the 80% enclosed-energy diameter. The AO-on budget is written in terms of rms wavefront error. Where possible, calculations are given in terms of analytic expressions, so that the error can be readily recalculated if the current baseline optical design parameters change. The error budgets include both a global telescope budget and a detailed budget for the primary mirror.

An important contribution to any adaptive optics error budget is the "fitting error" that describes the rms residual wavefront resulting from the limited ability of the deformable mirror to correct all spatial frequencies. Much has been studied and written about fitting errors. At the intersection of AO and a segmented primary, is the fitting error resulting from surface errors in the segments. We have completed roughly half of CELT Technical Note No. 1 that calculates the fitting error (as a function of deformable mirror actuator spacing) for random Zernike aberrations in an array of hexagonal segments.

Plan for Future

During the second quarter we will complete Technical Note No. 1 on fitting errors, and incorporate the results into the AO-on error budget. In addition, the draft error budgets will be completed and described in a CELT Report.

Task [3] Analyze and model wind influence on telescope

Description

Wind loads on the telescope will be studied. Loads during operations and survival loads on the dome will be addressed. During operations, there is the potential that wind loads directly on the top end of the telescope will cause the telescope to move and oscillate, causing image motion. In addition there is the possibility that wind loads on the primary itself will cause distortion of the primary mirror, occurring at frequencies higher than the bandwidth of the primary mirror active control system (ACS). Finally, wind loads on the dome itself may cause motion of the earth and hence the entire telescope on its pier.

We expect to use a combination of analytic tools, computer simulation, wind tunnel testing, and scaling from other observatories to assess the size of the wind disturbances.

Objectives

We will estimate the static wind speed distribution inside the dome (near the top end of the telescope down to the primary mirror) relative to the outside wind speed. This will be used to calculate the static force on the telescope. This speed distribution will be determined by some combination of

Measurements at Keck or other large telescope
Computer modeling
Wind or water tunnel measurements

We will estimate the dynamic effects of wind on the telescope as well, including spatial and temporal coherence.

Inputs

- Wind statistics for each candidate site
  (probability distribution of wind speeds on clear nights)
- Maximum 100 year wind speeds for each site (for survival study)
- Elastic properties of the soil under the dome for each site.
- Shape and cross section details of the top end of the telescope
- Power spectrum of wind at the site

Impact on Other Tasks

This will influence the telescope design, and the dome design

Status

Wind forces on the telescope may cause image motion in excess of allowed values. This is a critical unresolved issue for the CELT design The central problem is to estimate the dynamic forces on the telescope that may cause the images to move. There are several approaches to becoming informed:

1. Simple calculations of "static" wind force on the telescope can be made, using some assumed wind attenuation inside the dome and appropriate drag coefficients and Reynolds numbers. Then, given an assumed telescope stiffness, image motion can be estimated

2. There exists Gemini data with wind speeds at top of structure structure, along with external wind speed and orientation. Analysis of this data could be informative.
3. Computer-based simulations of the wind power spectrum inside the dome might be made.
4. Wind tunnel tests to estimate the wind power spectrum inside the dome might b e made
5. Wind speeds and turbulent spectrum might be measured at Keck.

Progress this Quarter

We have been exploring different sources of wind information, from books to experts to wind data on Gemini. This education process is continuing, so no definitive conclusions are yet available.

We have had preliminary discussions with Rose McCallan of LLNL concerning the likely effects of wind on structures. She recommends some combination of wind tunnel testing and computer simulations for reliable results.

Efforts to explore the use of an environmental wind tunnel at UC Davis, operated by Bruce White, have led to the conclusion that this wind tunnel is not appropriate.

We have made a preliminary examination of some of the Gemini wind tests (anemometers inside the dome of Gemini S). From this, our view is that wind speeds inside the dome at the top of the telescope will be reduced by about a factor of two from the outside air, with some dependence on the orientation of the dome slit with respect to the wind direction. Further, it appears that the wind speed near the primary mirror is reduced by roughly a factor of 10 relative to the outside wind speed. These results are compatible with those used in modeling Keck.

The upper "tube" of CELT is likely to be composed of trusses, rather than simple tubular beams. Discussions with McCallan and the reading of wind references (Simiu and Scanlan Wind Effects on Structures) suggest that wind forces on these trusses can be estimated by standard methods ($F = C_d \rho v^2 A/2$) and that cross talk between members of the truss will not significantly alter the result.

For some of the telescope designs in progress we have estimated the static wind loads and possible resulting image motion. The results suggest that wind will be a significant issue, driving the telescope design, but also that acceptable solutions might be possible.

Plan for Future

We will examine the Gemini data more carefully to better assess the static and dynamic characteristics of wind inside the dome.

We will work closely with McCallan to check our methodology and to assess which wind tunnel tests should be carried out and which computer modeling should be done.

The power spectrum of the wind will be estimated through some combination of Gemini data, simulations, and wind tunnel tests.

The likely forces on several telescope designs will be produced, and the likely resulting image motion will be estimated and fed back into the telescope structure design.

Task [4] Complete the optical design

Description

We will produce an optical design for CELT that includes a mathematical description of the optical surfaces and locations. The design performance of the system will be produced, including image quality, field of view, focal surface curvature, pupil positions, and sensitivity to misalignment.

Objectives

We will produce a Ritchey-Chretien optical design giving a 20 arc minute field of view with 0.5 arc second image quality (100% enclosed energy). Initial and final f-ratios are critical parameters that will be set, after a trade off study. The compatibility with planned adaptive optics systems for CELT will be carefully assessed and maximized. The sizes of the secondary and tertiary will also be carefully explored to understand their values in the optical design and the tradeoffs against difficulty of fabrication. Focal plane locations will be determined, taking into account the space required for science instruments

Inputs

Requirements on FOV, plate scale, and instrument sizes from working groups

Impact on Other Tasks

The optical design parameters are fundamentally related to the optimization of the segment polishing, mainly though the primary mirror focal length. The requirements of AO are also key inputs to the optical design, through the final focal length, focus position, and possibly special requirements for the secondary mirror. The telescope structure is driven by the optical design.

Status

A conceptual design exists with an f/1.5 primary (k = 90 m) and a back focal distance of 15 m with a final f-ratio of f/15. This design is sufficiently complete for current purposes.

Progress this Quarter

The secondary and tertiary sizes have been added to the optical design spreadsheet.

Plan for Future

When we have additional information on component costs and alignment sensitivities we will make a trade study of the value of changing the primary focal length. Information from the working groups may also cause us to re-evaluate the final focal length and back focal distance.

Task [5] Establish the segmentation geometry

Description

We will establish the thickness and radius (and thus the number of segments) of each segment. This will involve a complex tradeoff of many issues including predicted effects of thermal and gravitational changes, segment material costs, segment fabrication costs, segment passive support system costs, segment active control costs, impact on adaptive optics, re-aluminizing costs, and handling costs.

Inputs

None required for about six months. Then for a review, and possible revision of the geometry, we will require initial telescope and primary mirror error budgets and initial cost estimates for segment fabrication.

Cost estimates for segment fabrication and tests

Impact on Other Tasks

The definition of the segmentation is strongly inter-related to almost all other tasks.

Status

The segmentation geometry of the primary mirror is mainly defined by two parameters: the hexagonal segment sidelength (a) and the segment thickness (h).

The selection of a segment size, and hence the number of segments, depends on a complex tradeoff of many costs. A larger segment size (radius = a, thickness = h) increases the amount of asphericity required in the surface figure ($\sim a^2$), the gravity-induced deflections on a support, ($\sim a^4 / h^2$), the weight for handling ($\sim a^2 h$), and sensitivity to position errors in the array ($\sim a^2$). A smaller segment size increases the number of active control actuators and sensors, the complexity of a control wavefront sensor, and the complexity of the alignment and control software.

The selection of the segment thickness is also a complex compromise between costs. A larger thickness will require larger required forces for intentional deformation during fabrication, greater cost of the blank material, greater thermal inertia in the telescope, and a greater mass for the support structure (the telescope). A smaller thickness will require more support points to reduce deformations due to gravity.

We have not yet gathered estimates of these costs and cost variations. This will be required to make final informed compromises. Based on our experience with the Keck telescopes, we have adopted for now a baseline segment design. During the conceptual design phase this will evolve to final values for the radius and thickness. In the meantime we have adopted a segment radius of a = 0.5 meters and a segment thickness of h = 45 millimeters.

The resulting array contains 1080 segments. A central subset of 19 segments is deleted from the array since the light to them is blocked by the secondary mirror. This baseline array has an area = 702 m^2.

A discussion of some segment fabrication issues that affect the selection of segmentation geometry is given in CELT Report No. 5. "Primary Mirror Segment Fabrication for CELT", Terry S. Mast, Jerry E. Nelson, and Gary Sommargren, Proceedings of the SPIE, **4003**, 2000

Progress this Quarter

Progress on the selection of a segmentation geometry is being made through work on other tasks. Definition of baseline designs for segment actuators (Task 16), segment sensors (Task 14), and segment support (Task 9) will allow estimates of these component costs. Definition of the segment fabrication techniques and vendor estimates (Tasks 7 to 10) will provide additional cost estimates. All of these costs are required for the selection of a final segmentation geometry.

Plan for Future

Work on all associated costs will continue. We do not expect to have the required cost estimates until the end of the third quarter.

We also have the option of adjusting the positions of some peripheral segments to keep a closely circular periphery and at the same time to allow for convenient division of the array into subsets (full and partial "rafts" of 19 segments) for ease of handling. This adjustment, the inter-segment gap size, and the segment prism geometry are additional segmentation geometry issues that will be addressed.

Task [6] Establish the segment material

Description

The choice of segment material is important since most interesting materials are very expensive. The method of creating the optical surface on the segments will influence the options for material. For segment polishing, one needs either a directly polishable material or one that can be effectively plated. Glassy materials such as Zerodur or ULE are well known, but expensive choices. Aluminum is another potentially less expensive option that needs to be explored. More exotic materials such as SiC should also be investigated.

Objectives

Based on collected material properites we will assess the likely impact on segment thickness and mass, resulting telescope mass, and passive segment support. All these will influence, and may strongly impact, the overall telescope cost.

Inputs

Information on the material properties of candidate materials including E,ρ,α, k, internal stresses (needed for evaluating warping from cutting), availability, size limitations, long term stability, polishability, and cost. ESO reports on the evaluation of aluminum.

Impact on Other Tasks

Material choice is closely related to segment fabrication technique, methods of coating segments, segment passive support, telescope structural design.

Status

We currently assume the material of choice is Zerodur.

Progress this Quarter

A meeting took place with experts from Marshall Space flight Center (Scott Smith, Jim Bilbro) about the possibilities of other materials. They were enthusiastic about SiC, but it was clearly not ready for mass production, as no one is able to make even single pieces of 1 m size. They also supported Ni plated mirrors deposited to net polished shape against a master mold. Again, significant development would be required before it could be properly assessed.

Among the glasses, ULE is likely to be twice the price of Zerodur, with no significant advantages, and probably greater springing after cutting into a hexagon.

Plan for Future

The most likely alternative is Aluminum, and it will be studied in the next 3 months.

Task [7] Establish the segment fabrication vendor candidates

Description

Based on an initial definition of segment requirements we will discuss with all potential vendors the desired segment characteristics that they would be able to provide at minimum cost. This will require concentrated personal interactions with teams from each candidate vendor. Segment design and fabrication methods will be modified to find a low cost solution to segment fabrication.

Objectives

Definition of potential segment fabrication vendors and characterization of each in a fixed set of categories including experience, infrastructure, depth, etc.

Definition of a baseline fabrication scenario in enough detail to serve as a basis for a credible cost estimate.

Inputs

Documentation of planetary-stressed-mirror-polishing methods and fixtures.

Documentation of an in-process test option, including test error budget

Documentation of an interferometric test option, including test error budget

Initial progress on Task 2 Error budgets, Task 4 Optical Design, Task 5 Establish the segmentation geometry , and Task 6 Establish the segment material.

Impact on Other Tasks

This is a prerequisite for Task 8.

Status

We assume that the segments will be polished by planetary stressed mirror polishing as described in CELT Report No. 5. "Primary Mirror Segment Fabrication for CELT", Suitable vendors are needed.

Progress this Quarter

We visited several firms with Larry Stepp and Eric Hanson of Gemini.
We tabulate below the potential candidates.

Firm	**Location**	**visited**	**interested**	**capable**
Brashear LP	Pittsburgh, PA	yes	yes	?
Kodak	Rochester, NY	yes	yes	yes
Rayleigh	Tucson, AZ	no	yes	?
Raytheon	Danbury, CO	no	?	yes
REOSC	Paris, FR	no	yes	yes
SORL		no	?	?
Tinsley	Richmond,CA	yes	yes	yes
Zeiss	Germany	no	?	?
Zygo	Middlefield, CO	yes	yes	yes

Plan for Future

We will visit Rayleigh Optical next week with Larry Stepp of Gemini. We plan to make initial contact with the rest of the candidates in the 2nd quarter.

Task [8] Establish the segment fabrication cost

Description

Based on Tasks 5, 6, 7, 9 we will be able to establish an accurate estimate for all the processes required for segment fabrication. Interactions with candidate vendors will allow us to fine tune the processes and to generate a plausible cost estimate. Costs will come from vendor discussions and opinions.

Objectives

Determine a reasonable cost estimate for segment fabrication

Inputs

Design information, extensive vendor discussions and cost estimates.

Impact on Other Tasks

May influence the size of segments if the cost is size sensitive. This in turn will influence many other tasks.

Status

Current plans assume roughly $30K/m^2 based on earlier discussions with vendors. Their rough estimate was $15K/m^2.

Progress this Quarter

We have met with some vendors. We are working on essential related tasks (Tasks 9, 10), needed for further progress.

Plan for Future

In the 2nd quarter we plan to discuss with vendors the contents of the RFQ. We expect to include a stressing jig design, analysis of its performance, a prototype, and results of experiments with it. In the 3rd quarter we will initiate detailed discussions with vendors.

Task [9] Stressing fixture design, prototype and test

Description

We will design, build, and test a full-scale prototype stressing fixture. We will apply it to an aluminum segment, and measure the response, repeatability, and temperature and vibration sensitivities. If discussions with vendors show that this demonstration will have no significant impact on the cost estimates, then we can postpone the prototype and test phases.

Objectives

All candidate vendors have no experience with Stressed Mirror Polishing in a planetary polishing facility. Thus, this is likely to be a high cost-risk process for both CELT and the vendors. A detailed demonstration of the process will allow the vendors to make a credible estimate of the fabrication costs. Experience suggests that without such a demonstration all vendors will be required to provide very high cost estimates.

Impact on Other Tasks

The design (and perhaps the fabrications and tests) on Task 8 Establish the segment fabrication cost

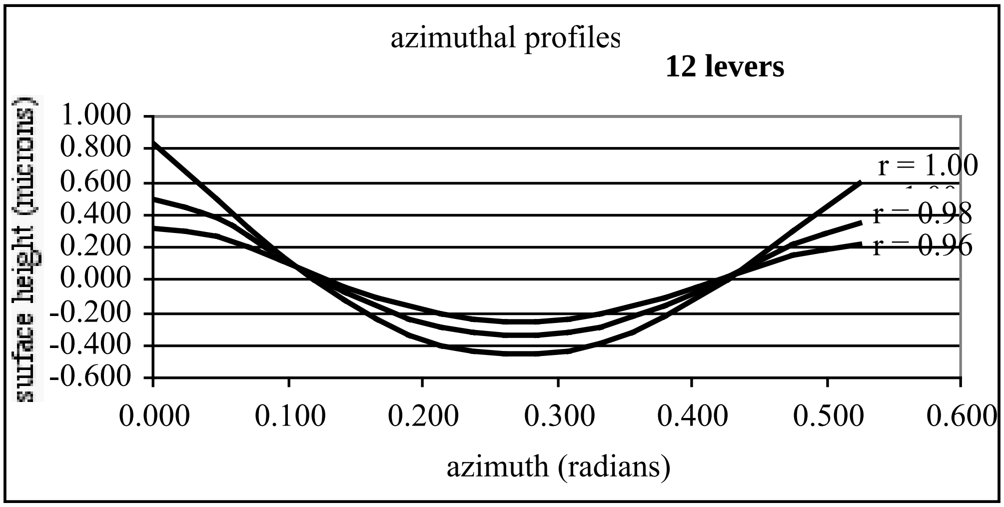
Status

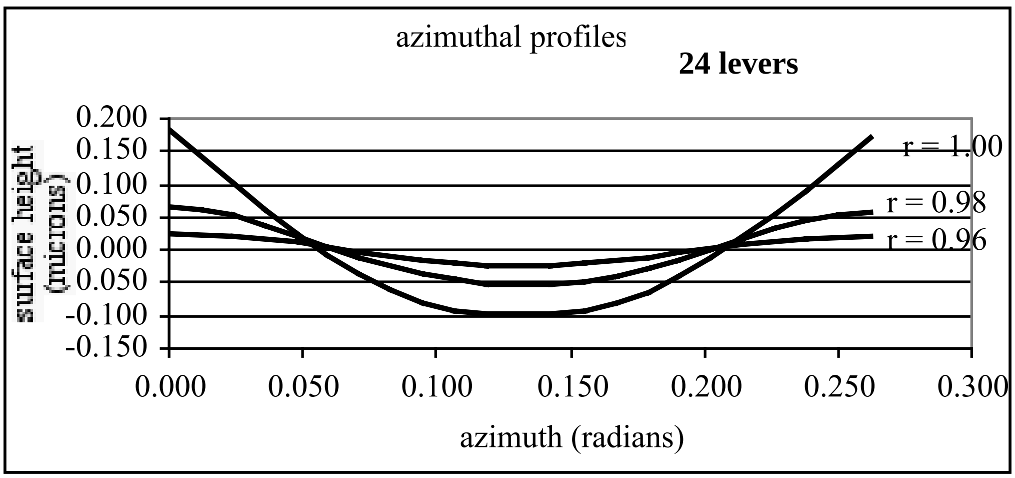
Some initial concepts for stressing fixture design are given in CELT Report No. 1 " Giant Optical Devices" Jerry Nelson and Terry Mast (Proceedings of the Backaskog Workshop of Extremely Large Telescopes, Anderson, T. ed, pp1-11, June 1999, Lund University and ESO) and in CELT Report No. 5. "Primary Mirror Segment Fabrication for CELT" Terry S. Mast, Jerry E. Nelson, and Gary Sommargren, (Proceedings of the SPIE, **4003**, 2000)

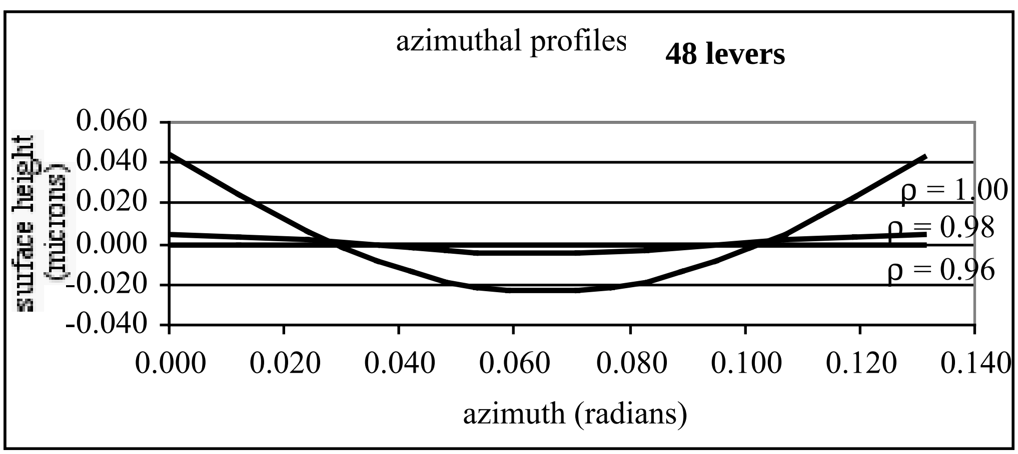
Progress this Quarter

We have nearly finished a report (CELT Report No. 11) giving equations for the required forces and moments for the stressing fixture, and giving an approximation to the expected performance. We have derived first order estimates of surface deformations close to the force/moment levers. The equations are general and we have considered examples of 12, 24, and 48 lever systems. The Keck segment blanks were stressed with 24 levers (96 attachment blocks). The following example figure shows the surface deformations between two of 48 levers. The stressing moments and forces assumed are those for the outermost CELT segment. (Requiring for the monomial coefficients ~19 microns of $\alpha 20$ and $\alpha 22$ and ~1 micron of $\alpha 31$). We have assumed a Zerodur blank with radius 0.5 meters.

We also estimated the induced internal stress in the glass, and they will be quite small.


azimuthal profiles
12 levers
surface height (microns)
1.000
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.600
0.000
0.100
0.200
0.300
0.400
0.500
0.600
azimuth (radians)
r = 1.00
r = 0.98
r = 0.96


azimuthal profiles
24 levers
surface height (microns)
0.200
0.150
0.100
0.050
0.000
0.050
-0.100
-0.150
0.000
0.050
0.100
0.150
0.200
0.250
0.300
azimuth (radians)
r = 1.00
r = 0.98
r = 0.96


azimuthal profiles
48 levers
surface height (microns)
0.060
0.040
0.020
0.000
-0.020
-0.040
0.000
0.020
0.040
0.060
0.080
0.100
0.120
0.140
azimuth (radians)
ρ = 1.00
ρ = 0.98
ρ = 0.96

The Figures above show examples for stressing fixtures with 12, 24, and 48 levers. The azimuthal profiles of the achieved-minus- desired surface are given for normalized radii $\rho = 1.00$, 0.98, and 0.96. The local sag between levers at the circular blank outer edge ($\rho = 1.00$) is about 1200, 280, 70 nanometers. It falls rapidly in from the outer edge. If a finite element analysis and a prototype test agree with these analytic approximations, then a circular blank radius of about 0.51 meters will be required for stressed mirror polishing.

Plan for Future

We expect to complete CELT Report No. 11 by the end of this year. We have also started work toward building and testing a half-scale prototype of the stressing fixture. Our goal is to design and test this prototype in the first three months of 2001. A suitable glass blank is available for our use at the Lick optical laboratory. Local surface deformations near to the force/moment lever attachment points will be measured using the 6-inch diameter beam of the Lick phase-measuring Zygo interferometer. The full aperture can be measured for a nominal fee using the LLNL 20-inch diameter Zygo. The stressing fixture engineering design needs to be made (December/January); the stressing fixture built (February), and then tested (March).

Task [10] Define the segment figure tests

Description

For mechanical measurement of segment surfaces we will build and test a system and use it to measure the performance of the prototype stress fixture of Task 9.

For optical tests of segment surfaces we have defined three possible options. For each option we will make a detailed optical test design, calculate the sensitivity to variations in all possible degrees of freedom and temperature changes. These will be used to construct segment testing error budgets and, if needed, revise the test designs. These and discussions with vendors will be used to establish cost budgets for segment testing.

Objectives

Document the process of selecting baseline options for testing the segments. These must include detailed error budgets that be communicated candidate vendors

Impact on Other Tasks

Significant input to Task 8 Establish the segment fabrication cost.

Status

An initial study of interferometric testing options is given in CELT Report No. 5 "Primary Mirror Segment Fabrication for CELT," Terry S. Mast, Jerry E. Nelson, and Gary Sommargren, Proceedings of the SPIE, 4003, 2000. Since the outermost segment surface surface will contain about 20 microns of astigmatism, the fringe density is expected to be high. Three options for reducing the fringe density were considered in the above paper: A Uses computer generated holograms, B Uses the test configuration geometry of the final segment use, C Uses a tilted lens to create a canceling astigmatic wavefront.

Progress this Quarter

The group at Livermore (under the direction of Gary Sommargren) has pursued the design of this test. Their work continues, and the conclusions below are tentative. They have considerable experience using a point diffraction test to measure X-ray optics surfaces to a precision of about 1 nanometer.

Based on their experience with the point-diffraction interferometry at LLNL, they have tentatively concluded that although the fringe density directly from the segments is high, it is still low enough to be used without reduction. A camera used at LLNL for this type of test uses a 1024 x 1024 CCD. With this camera the fringe density in testing the CELT segments directly will be close to, but not above, the Nyquist frequency, If necessary, it is certainly feasible to acquire or build a camera with more pixels.

The group at LLNL also investigated several optical designs for the focusing lens that reduces to size of the test to about six meters. They are currently favoring a single element lens with an asphere and spherical surface. They have also designed an imaging lens with four elements to image the segment on the CCD camera and to minimize shearing effects and distortion. They have written software to simulate the test; including segment surfaces, coordinate systems, measurement configuration, etc. The test will require a reference sphere with ~91 meter radius to be used to calibrate distortions in the interferometry. They are currently writing a report to be completed by the end of this year. To date a small fraction of the full project budget has been spent.

Plan for Future

The simulation software will be used to calculate sensitivities to errors and create an error budget. They are currently writing a report to be completed by the end of this year.
In the next quarter we at UCSC will begin to design, build, and test a protoype 2-dimensional array of probes to mechanical measure a prototype surface.

Task [11] Design the segment passive support

Description

We will design a passive support for the mirror segments, compatible with the active support system of three actuators and consistent with the thermal and gravitational disturbances. This must include supporting the segment against gravity in any orientation, while maintaining surface errors consistent with the error budget.

Objectives

For a specified segment size and material, we will devise a passive support system. This will include adequate axial support and lateral support. The segment deflections under gravity in any orientation will be calculated, and the design will produce adequately small deflections. The interfaces will be carefully described. This includes attachment to the segments and connection to the active control system actuators and mirror cell lateral support system as needed. The design will also include tolerancing of the support to ensure production is economical. The assembly process will also be addressed for feasibility. Thermal effects will be carefully investigated to ensure that performance is adequate, both for thermal effects between assembly and operations, and during operations. Durability of the system during segment installation, segment handling, segment exchanges, telescope lifetime, mirror cleaning, and mirror coating will be evaluated.

Inputs

Task 5 segment design, Task 6 mirror material, and thermal characteristics of the site.

Impact on Other Tasks

segment fabrication, mirror coating,

Status

Substantial progress (summarized below) has been achieved on the segment passive support by consulting engineer Steve Gunnels (Paragon Engineering,18231 Old Range Road, Tehachapi, CA 993561, 661.822.3358). Steve used finite element modeling to establish force and moment distributions that provide adequate segment support for both axial and lateral gravity loads. Neither of these requires holes to be cored into the glass as was done for the Keck segments. An analysis remains to be made to see if this conclusion holds for the expected operating temperature range.

Progress this Quarter

An initial meeting was held with Steve to define and clarify the segment support requirements listed below and define some initial questions to be addressed. Weekly telephone conferences have been used to discuss progress and to guide Steve's efforts.

Baseline Segment Design

Regular hexagon side length = a = 0.5 meters
Thickness = t = 45 mm
Density = 2.53 x 10^3 kg /m^3
Radius of curvature of front and back surfaces = 90 meters
Material: Zerodur
Elastic modulus = E = 91 GPa
Poisson ratio = ν = 0.24
CTE = 1 x 10^{-8} / ^{o}C

Baseline Support Requirements

Tolerance on surface deformations = 6 nm rms
Gravity : zenith angle range: 0 to 65 degrees
Range of control motion = 2 mm independently for each actuator
Temperature range: operations = 2 ± 8 oC
Temperature range: survival = -20 to + 40 oC
Humidity Range = 0 to 100% condensing
Support envelope = hexagonal by < 30 cm
Weight < 20% of 70 kg = < 14 kg
Stiffness = > 60 Hz
Lifetime = infinite
Maintenance = zero
Attachment to actuators = easy
Cost = < $2k
Vacuum compatible - yes
Allows easy segment removal

By decomposing the components of gravity we have separated the problem into separate axial support and lateral support problems. The Keck segments are supported by two separate subsystems that address these separate components. For CELT we have explored supports that similarly include two subsystems and also an integrated system, where a single support design addresses both components of gravity.

A number of modifications of the integrated design were studied and all gave large (~ 1-2 microns peak-to-valley) deflections. We are now concentrating on a separated subsystem design where each subsystem is yielding peak-to-valley deformations of ~10 nm.

Once the performances of axial support and lateral support subsystems are established, we can combine their effects. This combination will include the expected telescope operating zenith angle range (currently 65 degrees), an allowed error that increases with zenith angle (due to atmospheric seeing), and possibly ion-figuring removal of the surface error expected at some optimum zenith angle. This optimization will take into account both the AO-off and AO-on modes of telescope operation, and in particular, the deformable mirror response to the axial- and lateral-support induced aberrations ("fitting error").

The final error budget for the segment support is not established, but is expected to be of order 5 nm rms. In this conceptual study we want to learn if potential simple and low cost designs are possible.

Background

The concept design of the CELT mirror segment supports began nearly two months ago. The goal has been to develop a passive, robust and economical support system which acts solely from the back surface using 18 axial support points and which limits the surface distortion of the baseline segment to about 5 nanometers (nm) root-mean-square (rms) due to rotating in the gravity field for zenith angles from 0 to 65 degrees.

In pursuit of this goal 29 computer finite element models have been used to calculate surface distortion under various support arrangements and load conditions. The models have ranged in size up to 14,000 degrees of freedom with as many as 10 load cases each. In addition, numerous 2D CAD layouts have been made of potential mechanical designs. Approximately 12 brief reports have been written summarizing the results of the work thus far.

Axial Support

A hexagonal segment has twelve-fold symmetry (a triangular region can be folded around the optic axis twelve times). For an 18-point support there are therefore 1.5 supports per triangular region. This defines 4 topologies for the axial support: full support center + half support edge A; full support center + half support edge B; two half supports edge A + half support edge B; one half support edge A + two half supports edge B. A half support is one shared by either adjacent triangular region.

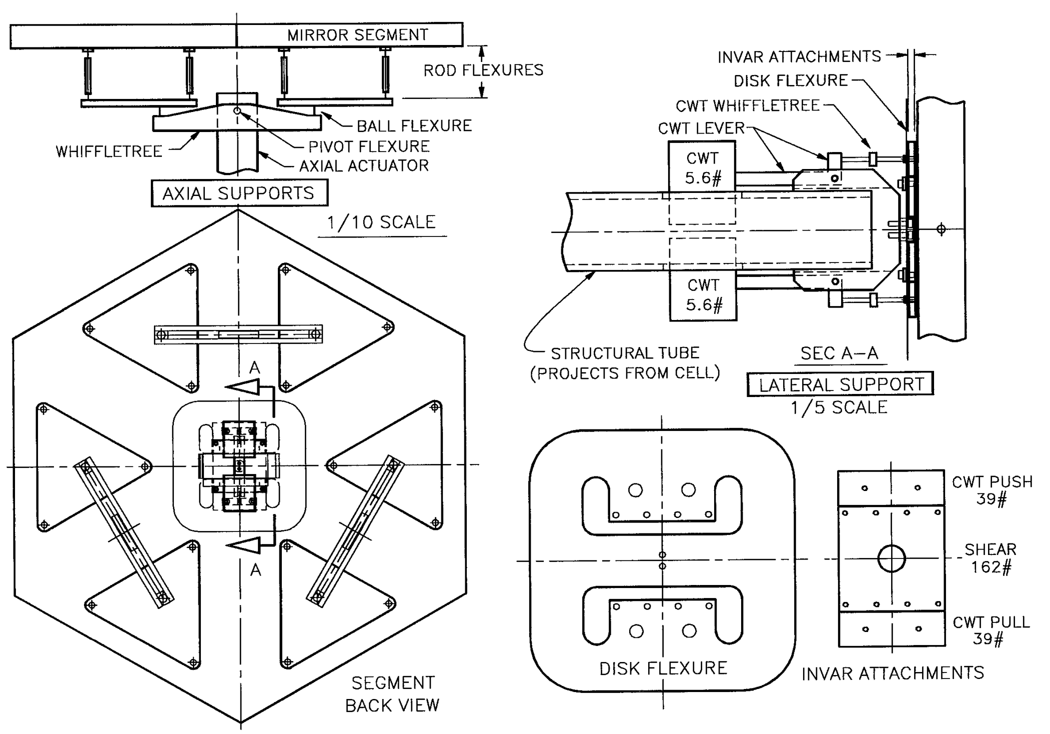
All four topologies were analyzed and the support locations optimized to minimize the peak-to-valley (p/v) surface distortion under 1 g zenith gravity. The rms for these surfaces was subsequently calculated. For the four topologies the p/v surface distortion ranged from 21.1 to 29.3 nm. The rms range was 5.06 to 7.11 nm. These rms values likely have a small error, since the calculation doesn't compensate for variations in mesh density in the finite element models. The two topologies with three half supports on the edges define mechanical support systems that are not symmetric with respect to the hexagonal shape of the segment. In addition, one of the symmetric topologies was revised allowing more droop of one corner (the point in the hexagon). This lowered its rms from 6.8 to 6.14 nm, while the p/v increased from 29.0 to 38.3 nm. Additional optimizing and refined rms calculation including mesh density compensation and other effects are planned which may lower the axial support errors.

The conceptual design axial support hardware is shown in the left views of the drawing below. As shown, each of the three axial actuators supports a whiffletree which equally distributes the axial force to two triangular plates. With the force applied to each triangular plate via the ball flexure then distributed to three points each on the segment via the rod flexures, the 18 axial support forces are accurately defined and the system is kinematic.

Lateral Support

If the mirror is supported at one or more points on the back surface and lateral (horizon) gravity applied, a moment develops due to the axial eccentricity of the lateral force with respect to the c.g. location in the central plane of the segment. Early analysis showed that, if the moment was not compensated (i.e. was reacted only by two opposing axial actuators at a considerable distance) the p/v distortion of the segment would be hundreds of nanometers or more. In addition, through considerable optimization it was learned that the lateral (shear) force should be applied over a relatively small area and that the moment compensation (a set of push-pull forces) is best done just outside, or beyond the footprint of the shear force application.

After numerous optimizing computer analyses (the results of which are summarized in the weekly reports), a lateral support geometry was arrived at which yielded very good results. Shown in hardware in the right views of the drawing below, the shear force is distributed by a 4" square invar plate and the moment compensation done by adjacent push/pull invar plates above and below. All three plates will be bonded to the segment with silicone or epoxy adhesive. The push and pull forces are established by an astatic levered counterweight system as shown. In addition, the small weight of the invar attachments is compensated under zenith gravity by the small eccentricity of the 5.6 pound counterweights with respect to the lever pivot.



The distortion of the segment due to this support was calculated to be 10.5 nm p/v, with an rms of 1.8 nm.

Summary

The concept design of the axial and lateral supports is close to meeting the gravity distortion goal for the baseline segment as stated above. This design appears to be simple and cost effective. Additional optimizing of the axial support locations and refinement of the rms calculation method will likely result in complete satisfaction of the goal. Further analysis is required of the disk flexure, axial rod flexures and glued invar attachments to quantify other errors and determine whether the system is adequately robust.

However, this initial study did not include the requirement that segments be interchanged from one 60-dgree sector to another. Therefore, the design will be generalized to accommodate any segment azimuthal orientation.

Plan for Future

The design of the central support and counterweights will be modified to allow segment interchange from primary mirror sector to sector. The thermal sensitivity of the design will be calculated. We expect this conceptual design effort to be completed during the second quarter.

Task [12] Develop algorithms to combine Displacement Sensor and Telescope-Control Wavefront Sensor (TCWS) readings

We have considered and written code to realize a first order algorithm to combine telescope wavefront sensor and active control system data. This algorithm is not intended to be optimal in any sense, but it provides a simple means to combine these two separate inputs in order to estimate the overall system response at a level of accuracy that is appropriate to this stage of the design study.

The algorithm works as follows: Construct the ACS control system matrix (A matrix) as usual. Use Singular Value Decomposition to construct the SVD modes of the system. Each mode is a vector of 3240 actuator values (corresponding to the 1080 segments), and these vectors form a complete and orthonormal set which span the space of all possible configurations of the telescope primary mirror, with the exception of the three rigid body degrees of freedom (which we ignore for now) and focus mode. These modes can be ordered in decreasing order of the error multipliers; this is roughly equivalent to increasing order of spatial frequency. For completeness, we call the non-singular mode with the highest multiplier "mode 2" and reserve "mode 1" for focus mode.

Now for the twenty or so lowest modes, we convert the actuator values to segment tip/tilt errors. We define a wavefront sensor by mapping the 1080 segment pupil onto a Shack-Hartmann array. For the moment we take the latter to be a 5-ring hexagonal array of 90 lenslets. Once the mapping is defined, we can calculate the centroid error for a subimage corresponding to a given lenslet by averaging over the tip/tilt errors of the segments which are mapped into that lenslet. We again use Singular Value Decomposition to determine the error multipliers which relate centroid error (in arcseconds) to the amplitude of the corresponding mode. Note that while ACS error multipliers are dimensionless numbers, the wavefront sensor (WFS) error multipliers are in units of microns (of actuator error) per arcsecond (of centroid error). To put WFS and ACS noise multipliers on equal footing, we multiply the former by the nominal ratio of WFS centroid uncertainty (one dimensional) to sensor noise level. We currently estimate these parameters as 30 mas and 6 nm respectively, so that the appropriate ratio is 5 arcseconds per micron.

The estimate of 30 mas was obtained using the equation in Hardy, incorporated into an Excel spreadsheet by Rich Dekany. The inputs were as follows:

wavelength	0.7 microns
subaperture diameter	3.0 meters
integration time	0.03 seconds
subimage width	0.5 arcseconds
V magnitude	18.5
read noise	3.0 counts per pixel
sampling	4.0 pixels per subimage

These values yielded a centroid error (one dimensional) of 26 mas.

The accompanying plots show the individual mode error multipliers and residual error multipliers for the ACS alone (supplemented by the single focus mode measurement from the WFS) and for the combined WFS/ACS system. Note that these are typical values only. There has been no attempt to optimize anything.

At the time of this writing the plots for this task were unavailable for inclusion. They will be presented at the CELT Steering Committee meeting and will be incorporated here later.

Task [13] Study the spatial frequency response of the primary mirror control

1. Timing of the Matrix Inversion

An error was made in the description of the Conceptual Design Plan for this task: it was incorrectly stated that the computation time for the inversion of the control matrix on an Alpha 21264 (667 MHz) computer was over 24 hours via Singular Value Decomposition (SVD). The actual time should have been 6 hours. [The 24 hour figure was for a model of the OverWhelmingly Large Telescope (OWL).] Nevertheless, we have still been working to reduce this computation time in the interest of improving the efficiency of our design studies. The SVD inversion now takes under 2 hours; the major improvement has resulted from replacing the Numerical Recipes libraries with those of LAPACK, an efficient linear algebra package (see http://netlib2.cs.utk.edu/lapack/). A further reduction to 32 minutes was achieved using the Lower/Upper (LU) decomposition technique (again from LAPACK), but LU does not produce the modal decomposition that SVD does. Since at the moment it appears that modal decomposition may be integral to the primary mirror control, we are not pursuing LU decomposition of the control matrix further at this time.

2. Control Law

As discussed in the Conceptual Design Plan, the bandwidth of the control loop for the CELT active control system may be limited by the time required to do the matrix multiply (of the pseudo-inverse of the control matrix times the sensor data vector); this currently takes 5 seconds on the Alpha 21264 (667 MHz). A possible way around this limit is to replace the exact (global) control law with an approximate (local) one in which one considers only the effect of actuators in a neighborhood of a given sensor as one attempts to drive that sensor to its desired reading. Mathematically, one is exploiting the sparseness of the control matrix. Because the number of actuator- sensor linkages one considers are thus drastically reduced, these local actuator moves can be calculated much faster than for the full global control. Because the local control law is only approximate, one must iterate the solution, but if the convergence is sufficiently fast, there can still be a considerable savings of time.

As first step to exploring such alternative control laws, we have calculated the "condition number" of the control matrix for CELT, as well as for several smaller telescopes, all the way down to Keck. As discussed in Numerical Recipes, the condition number of a matrix is defined as the ratio of the largest to the smallest non-vanishing SVD error-multiplier. Generally speaking, the larger the condition number of a sparse matrix, the slower and less accurate is the convergence of the local schemes described above.

Condition Number for Segmented Telescope Control Matrices

Rings	Condition Number

3 (Keck)	85.9
4	133.7
5	193.8
6	265.9
7	350.1
9	554.4
11	806.7
15	1455.5
20 (CELT)	2206.6

A better figure of merit in this context would probably be the square of the condition number, which is the condition number of the transpose of the control matrix times the control matrix itself. The very large condition number for the CELT ACS is somewhat discouraging in this regard.

To get a feeling for how the size of the condition number translates into the difficulty of producing a local control law, note that in our Phase Discontinuity Sensing algorithm at Keck, we use just such a local control law. The template-based scheme used there essentially just looks at nearest neighbor segments; the control matrix is never inverted. The control matrix for this restricted phasing problem (36 x 84) has a condition number of 4.6 and the approximate control law was straightforward to implement. On the other hand, for the full tip/tilt/piston problem (108 x 168), the condition number is 153.7 and we never succeeded in deriving a similar local control law.

Note that if the lower spatial frequency degrees of freedom are off-loaded from the active control system to the telescope control wavefront sensor, that will tend to stabilize the former system and should act in the direction of making it easier to come up with a local control law. If the lowest 20 degrees of freedom are thus off-loaded the effective condition number is reduced from 2207 to 215. This would seem to offer the best chance of successfully exploiting the sparseness of the control matrix.

Task [14] Segment Displacement Sensors (design, prototype, test)

Description

> This a potentially very expensive and complex item for CELT. About 6000 displacement sensors are required for segment stabilization. We will create an in-house design and also complete a thorough survey of commercially available devices. If no commercially suitable devices are available and affordable, we will prototype and test the in-house design.

Objectives

> Complete a thorough survey of commercially available devices
> Create an in-house design. If no commercially suitable devices are available and affordable, prototype and test the in-house design

Status

Initial Sensors design concepts are given in CCELT Report No.6 "Segmented Mirror Control System Hardware for CELT", Terry S. Mast and Jerry E. Nelson (Proceedings of the SPIE, 4003, 2000).

Progress this Quarter

No progress has been made on displacement sensors during this quarter. At UCO/Lick research personnel have been strongly interested in refining the design, building prototypes, and testing them. However, they have been fulfilling commitments to other projects.

Plan for Future

Interested personnel at UCO/Lick will begin work on sensors at the beginning of the second quarter. If this is still not possible, we will pursue hiring other engineering staff.

Task [15] Design Telescope-Control Wavefront Sensor (TCWS) hardware

Description

As noted in the description of Task 12, CELT will require a Gemini- or VLT-style Telescope-Control Wavefront Sensor (TCWS) for monitoring the lowest ten to thirty spatial frequency modes of the primary mirror. The baseline assumption is that the TCWS will be a Shack-Hartmann-type camera in which the primary mirror is re-imaged onto a lenslet array, producing an array of stellar subimages (containing wavefront gradient information) on a CCD. The current task will determine the conceptual design parameters of the TCWS.

Progress this Quarter

Our initial effort on this task is to learn about wavefront sensors being used on large telescopes. The first to be researched is the wavefront sensor for the Gemini telescopes. Results are given in "The Gemini active optics wavefront sensors - guidelines for the CELT telescope-control wavefront sensor" (Schoek and Chanan, October 2000)

Task [16] Segment support actuators (design, select, test)

Description

The segment support actuators are potentially very expensive and complex. About 3300 segment actuators are required. We will make a thorough survey of the availability and cost of commercial actuators. We will design a lever-actuator system in order to expand the range of applicable commercial actuators. Every effort will be made to define the actuator requirements to minimize the costs: acquisition, fabrication, and maintenance. Robustness of candidate actuators will be tested, since the active control system has zero redundancy for actuator failure.

Objectives

Develop or acquire an adequate displacement sensor

Status

Initial requirements and concepts for segment support actuators are given in CELT Report No. 6 "Segmented Mirror Control System Hardware for CELT", Terry S. Mast and Jerry E. Nelson, Proceedings of the SPIE, **4003**, 2000. Substantial progress has been made this quarter and is summarized below.

Progress this Quarter

A consulting engineer, Alan Shier (The Pilot Group, 3130 Foothill Blvd., Unit 1, La Crescenta, CA 91214, (818)790-7481), was hired to work on actuators. An initial meeting was held with Alan to define and clarify the actuator requirements listed below. Weekly telephone conferences have been used to discuss progress and guide Alan's efforts.

- 1080 segments + (1080 / 6 =) 180 spare segments
- 3 actuators per segment to control piston/tip/tilt of the segment.
  [= 3 * (1080 + 180) = 3780 + spares $\Rightarrow$ ~ 4000 actuators]
- Each actuator connects to the segment through a whiffletree
  which is used to more uniformly distribute the load to the segment.

Requirements

	Keck	CELT
Range	> 0.6 mm	> 1.2 mm
Rms position error average over 20 minutes	< 20 nm	< 7 nm
Tracking rate		2 to 10 moves / sec
Slew rate	> 10 microns / sec	> 10 microns / sec
Transverse load capacity	> 14 kg	> 5 kg
Axial load capacity	> 150 kg	> 30 kg

Axial stiffness	> 5.9 x 107 N/m	> 1 x 107 N/m (~100 Hz resonance)
Transverse stiffness	> 12.7 x 105 N/m	> 1 x 105 N/m
Local average power dissipation	< 10 W	< 2 W
Lifetime	ten ~ 30 nm moves / second	continuously for 10 years
Survival temperature		2 ±20 oC
Operating temperature		2 ±8 oC
Operating humidity		0 to 100% condensing
Electrical shock resistance		yes
Dust protected		yes
Installation and Removal Ease		yes

Alan has researched commercial actuators, designs requiring a hybrid of an in-house design with a commercial actuator, and an in-house design.

In principle there are two categories of actuators: those that directly address the requirements, and those that drive a motion reducer that move the segment. Using a motion reducer 1) greatly expands the range of candidate commercial devices that can meet the range and load requirements, 2) greatly reduces the sensitivity to stiction (micro-welding) and breakaway problems, and 3) reduces the likelihood of local wear that might reduce the lifetime.

We have now identified five types of motion reducers 1) hydraulic (used in the Keck actuators), 2) differential screw, 3) tradition lever, 4) elastic reducer, and 5) an over-acting lever.

A hydrualic motion reducer provides a 24 to 1 motion reduction the Keck actuators.
Differential rolling screws are probably too expensive
A traditional lever design with a flexural pivot is probably good for ratios of order 10, but perhaps too sensitive to errors for the ratios of order 50. An "elastic reducer" (using the motion induced by a moment at the end of a beam, based on a design of Alson Hatheway). This looks promising for large reduction ratios. In this design a commercial displacement actuator with a range of order 50mm is used to compress a spring to provide a force that drives horizontally the end of a vertical beam. The opposite end of the vertical beam is attached to, and applies a moment to, the end of a horizontal beam. This elastically bends the horizontal beam inducing a small vertical motion of the beam end, and this vertical motion drives the segment support.

Alan has submitted the following summary of the work to date.

Present Best Candidates

- Modified Keck Actuator (ball or roller screw and elastic-reducer).
- Feedback voice coil (Lorell/Aubrun).
- Commercial motorized micrometer and conventional lever.

Commercial Actuators Considered

Motorized micrometers:

Lever Requirements: from 3:1 to 25:1

Concerns: Life and backlash

Source: Oriel, Melles Griot, Newport, Physik Instrumente

Cost: From $900 to $7k plus electronics for basic device alone.

Piezoelectric Inchworm

Lever Requirements: none - good motion resolution.

Concerns: incapable of required loads and life.

Source: Burleigh.

"Pico Motor" Piezoelectrically driven screw

Lever Requirements: : 10:1 lever.

Concers: May require sensor at the output since incremental travel is load dependent. Existing device generates copious RFI—could likely be shielded, though.

Source: New Focus.

Cost: $ 500 plus electronics for basic device alone.

Custom/Semicustom Actuators Considered

Precision ball screw and lever

Lever Requirements: Could possibly function with 3:1 lever.

Concerns: Screw lubrication and micro-welding a particular concern. Could possibly function with high ratio lever (>30:1). Eases lubrication problem.

Source: (Steinmeyer)

Cost: uncertain yet.

Modified Keck Actuator

Roller or ball screw with Hatheway-style elastic reducing mechanism (>40:1 reduction).

Could be feasible (see Engineering Analysis and Evaluation below)

Actuators Possibilities that are Set Aside for Now

All coarse/fine two stage devices

Likely require sensor at the output.

More complex, making life and cost requirements difficult to meet.

Differential Screw/Ballscrew/Rollerscrew

Additional complexity may not be necessary.

Piezoelectric stacks

Currently available travel is insufficient.

Piezoelectric Inchworm development effort

Cost prohibitive at this point (Burleigh).

Other Possible Actuator Sources

(Interest expressed. No substantial response yet received)

Ball Aerospace
TS Products (HET actuators)
IDC Motion (Green Bank actuators)
Ken Lorrell/Jean Aubrun (position feedback voice coil)
Blue Line Engineering (Adaptive mirrors, HET mirror sensors)
CSEM (Switzerland)
UA/Brian Cuerden (impulse screw)

Brief Sensor Vendor Survey (1.2 mm range, 4 nm resolution)
Kaman, Eddy Current Sensors
Require some development, but could work.
Cost a concern: $800/channel.
ASL Instruments, Cylindrical Differential Capacitors
Technically suitable
Cost unknown.
Others, either technically unsuitable, costly, or both:
MTI and Lion Precision (Plate capacitive sensors)
Transicoil (LVDT)
Heidenhain (5 nm glass-scale gage head)

Engineering Analysis and Evaluation
Modified Keck actuator (after Hatheway)
Size, mass could be acceptable
Cost borderline high. May yield to further work.
Performance, life likely to be good.

Sensor feasibility and noise analysis for 4 nm resolution over 1.2 mm stroke.
First order noise and quantization analysis performed. All OK.
Power an issue (fast, high resolution ADC. Cannot be "delta-sigma" device.)
If required, it appears that a cost-effective device could be designed with commercial parts.

Plan for Future

Alan will continue to pursue our Present Best Candidates
- Modified Keck Actuator (ball or roller screw and elastic-reducer).
- Feedback voice coil (Lorell/Aubrun).
- Commercial motorized micrometer and conventional lever.

This effort will include his own conceptual engineering, interacting the Lorell and Aubrun, and communication with potential vendors.

Task [17] Design camera required to determine desired sensor readings

At the Keck telescopes, the desired sensor readings are determined by a Shack-Hartmann camera, known as the Phasing Camera System (PCS). In addition to this task, which can alternatively be thought of as aligning the segments in piston and tip/tilt, PCS can also zoom in on individual segments (or groups of seven segments) to determine the segment surface figures which are needed for warping harness adjustments. Although there exist other techniques which can in principle accomplish these tasks (e.g. curvature sensing, the Gerchberg- Saxton algorithm, phase diversity), PCS has the distinct virtue that it has been successfully proved on a large segmented telescope. While we are investigating some alternative techniques in the context of CELT alignment issues, here we explore the issues involved in scaling up Keck PCS to a CELT PCS.

1. Tip/tilt alignment

PCS has two distinct advantages over the image stacking techniques (e.g. the MAlign algorithm) which are also used for segment tip/tilt alignment at Keck. These advantages are (1): the fact that PCS is passive, while image stacking relies on the Active Control System to perturb the segment tilts in a controlled way, and (2): PCS can distinguish telescope focus from focus mode, whereas image stacking cannot. The passivity of a PCS-type system is a particularly attractive feature during the early phases of telescope commissioning, when the ACS cannot necessarily be counted on to perform up to specifications; this is probably even more important for CELT because of the large increase in complexity of the corresponding ACS. The ability to distinguish focus and focus mode is arguably somewhat less important for a CELT PCS than for Keck because the ratio of segment diameter to telescope diameter is smaller. However, it is still important to be able to distinguish these two modes - otherwise the focus mode error could gradually grow without limit.

In order to make the focus mode measurement, a CELT PCS would have to have more that one Shack-Hartmann spot per segment. For the sake of definiteness, we assume a hexagonal arrangement of seven spots per segment. This would correspond to 105 spots across the pupil, or 131 spots across the full CCD array, if we allow a 10% margin around the edges of the detector. This corresponds to 16 pixels from spot center to spot center on a 2K by 2K array. The image scale in the corresponding PCS mode is 5.1 pixels per arcsecond, so this separation is equivalent to about 3 arcseconds; this is a comfortably large value. We conclude that a 2K by 2K CCD would therefore be adequate for this purpose. For early operations, however, or for post-segment-exchange alignment, the 3 arcsecond separation is uncomfortably small, as the corresponding alignment errors could easily exceed this value. A second tip-tilt mode with one spot per segment could increase the separation by about a factor of sqrt(7) to 8 acseconds. [Keck PCS in fact employs such a mode, which although it is needed infrequently, is absolutely crucial on those occasions when it is needed.] We could pick up an additional factor of 2 by going to a 4K by 4K CCD.

2. Phasing

The Shack-Hartmann phasing mode of PCS utilizes an array of microprisms as the key optical element. Although the array of microprisms used at Keck would probably be difficult to expand by large factors, we have shown in a series of laboratory measurements that commercially available microlenslet arrays are now of sufficient quality to constitute a viable substitute for microprisms. Thus, for Shack-Hartmann phasing of very large telescopes, the principal concerns have mainly to do with available area on the detector and with computation time.

We can estimate the required CCD size for Shack-Hartmann phasing of CELT as follows. At Keck the Shack-Hartmann image scale is 6.77 pixels per arcsecond and each subarray corresponding to the diffraction pattern from an intersegment edge is 33 pixels or 4.88 arcseconds on a side. Nearest neighbor patterns are about 60 pixels or 9 arcseconds apart. These numbers are not optimal for phasing a very large telescope, where the CCD would be much more crowded with images. The Keck diffraction patterns actually spill over the boundaries of the subarrays to some extent; nearest neighbors should probably be at least 6 arcseconds apart. Simulations suggest that the Keck image scale is overly generous and a scale of 4 pixels per arcsecond would probably suffice. For CELT there are about 70 nearest neighbor diffraction patterns across the full aperture phasing image. At the above image scale and nearest neighbor sepa- ration this corresponds to 1680 pixels. Thus allowing for appropriate margins, a 2048 by 2048 detector should be adequate.

For CELT the computation time would likely be dominated by the need to invert the very large phasing matrix, nominally 1080 (segments) by 3102 (edge measurements). We have generated the appropriate matrix and inverted it via a Singular Value Decomposition (SVD) algorithm in about 15 minutes using a 670 MHz Alpha 21264 processor. Straightforward improvements to the algorithm, not yet incorporated, should reduce this to about 5 minutes. Note that SVD algorithm accomplishes not only the desired matrix inversion, but also a modal decomposition of the general solution of the linear problem. This latter decomposition may be an essential part of the telescope active control system, but it should not be necessary for the solution of the phasing problem. Thus we should be able to replace the SVD algorithm in the present problem with the so-called Lower/Upper (LU) decomposition to construct the inverse of the phasing matrix. We estimate that an efficient LU code (not yet implemented) will reduce the calculation time for this matrix inversion to 2 minutes or less. Further increases in computer speed over the next 5 to 10 years should render the phasing computation time completely negligible.

3. Segment Figure Measurements

At Keck, the segment figure measurements are made with 217 Shack-Hartmann spots across a segment (for individual segments) or 127 spots across a segment (for a set of seven segments). For CELT it would probably be convenient to organize the segment measurements by rafts or possibly by sets of seven rafts. For a set of seven rafts, at the density of spots calculated in the tip/tilt mode above, there would be ~1000 spots per segment, which is an order of magnitude more than necessary. We conclude that the segment figure mode will not drive the design of a CELT PCS camera.

For several reasons it has not proved possible to automate the pupil registration function in the Keck PCS segment figure measurement process - this is the only mode where this function must be done manually. As a result there is a considerable overhead in making these measurements at Keck, and the need to do this 36 separate times in order to cover the full Keck pupil one segment at a time is considered to be at the limit of practicality. [This was the motivation for a seven-segment figure measurement mode at Keck, currently being implemented, which can cover the full primary with six measurements.] The CELT primary will likely have 54 full and 6 partial rafts, so the one raft at a time approach would probably be impractical. On the other hand, one could cover the primary with 13 groups of 6 rafts each, which would probably be acceptable.

Additional Telescope Design Activities

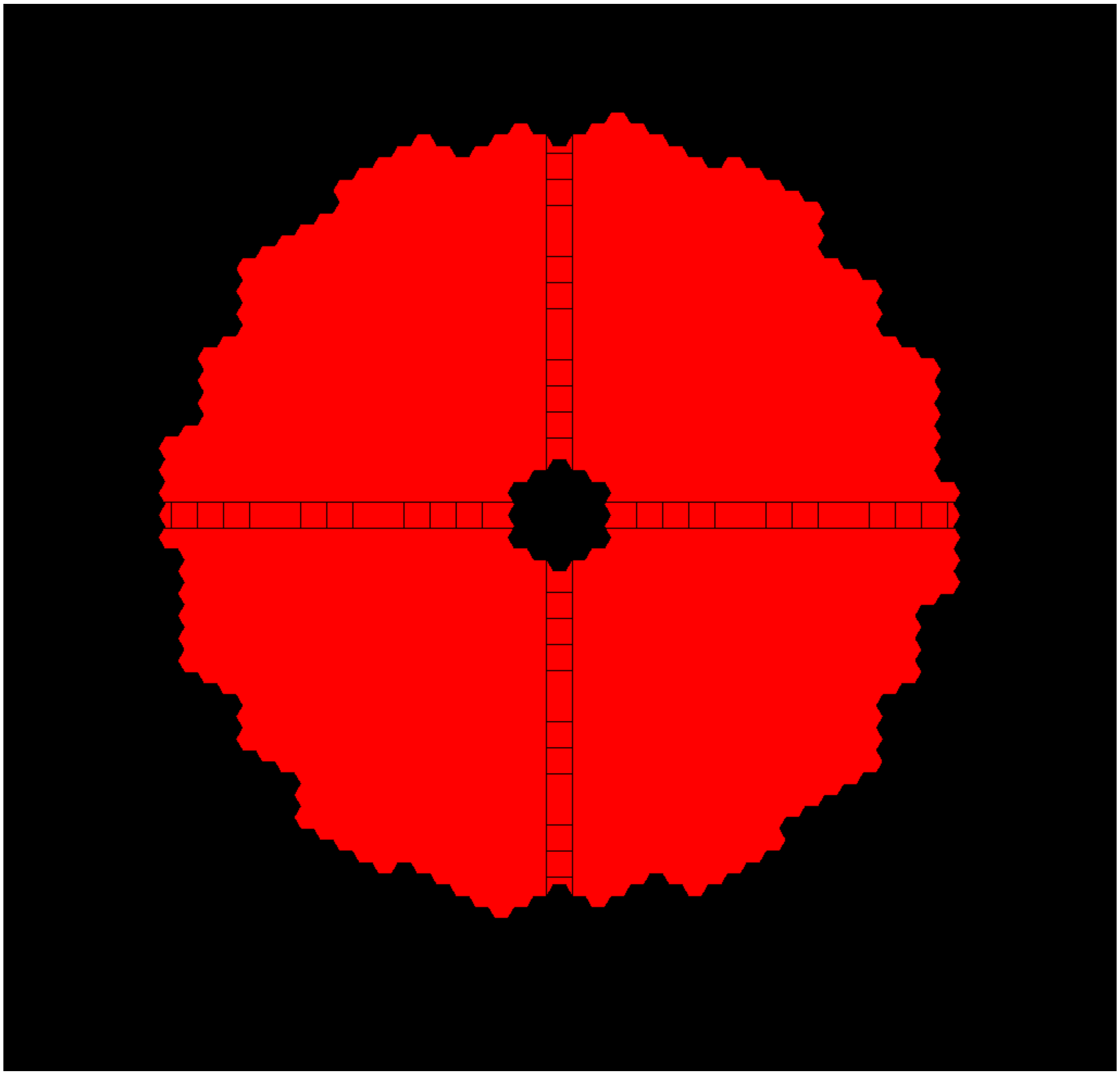
CELT Diffraction Patterns

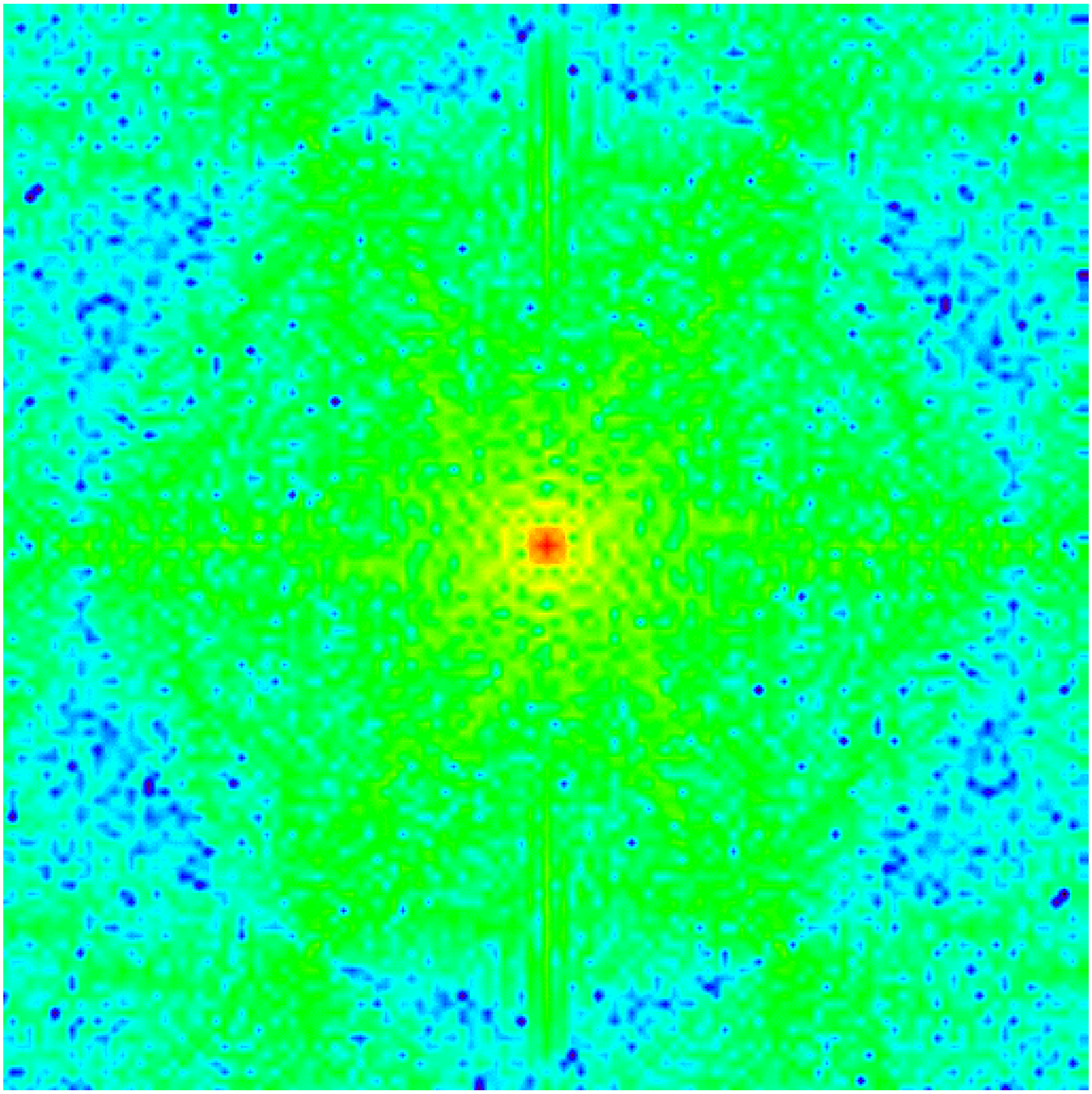
We are developing a code to evaluate the diffraction consequences (in mono-chromatic light) of various CELT segmentation geometries, segment alignment and figure errors, and secondary mirror support structures. The code curently supports:

- segment piston errors
- segment tip/tilt errors
- segment second order wavefront errors
- global focus errors
- rudimentary secondary support structures
- seeing (in the long term exposure limit only)

We are in the process of porting the code to a faster computer with more memory, so that larger Fast Fourier Transform arrays can be included. In its present implementation we are limited to 1024 x 1024 arrays; this in turn limits our resolution in the aperture plane. We plan to extend this to 8K by 8K or 16K by 16K in the near future.

As an example of this code we include a figure showing the diffraction pattern for a perfect primary with a simple secondary support structure (also shown). The missing cross bars in the aperture plane are caused by insufficient sampling





Task [18] Define secondary and tertiary physical & performance parameters

Description

The secondary mirror or mirrors is a fundamental part of the telescope design. We will assess the need for multiple secondaries, and what their desired optical properties are. We will assess the impact of secondary size on science performance. We will study the tertiary mirror requirements. We will also investigate field rotation issues and conceptual design options for addressing them.

Objectives

We will produce optical designs for two secondaries, one rigid for optical and near IR applications, a second one for an adaptive secondary. Surface and alignment specifications will be produced, and a weight estimate for each, including the entire support system. A cost estimate will be produced.

Inputs

The secondaries are fundamentally related to the primary and final f-ratios, as well as the location of the final focus. The design of the AO systems is also closely related. Size, location, weight, position tolerances will drive the structural design of the telescope.

Status

The current baseline optical design has a secondary mirror, 3.64m in diameter. The assumed weight of the mirror and support system and suitable attachments is 20 tons.

Progress this Quarter

The spreadsheet that describes the optical design can readily calculate new optical element size when any design parameter is changed. The tertiary has now been included in this spreadsheet. The current tertiary is approximately 3.0 m x 4.3 m. Opinions about feasibility of the secondary and tertiary are based on the design and costs for the 4.2-meter-diameter SOAR primary mirror that will cost about $10M including mirror, polishing, passive and active support.

Plan for Future

In the next quarter we will define the mirror sizes (once the optical design has frozen) and generate a strawman support and contact Raytheon (who is fabricating SOAR) for technical comments and a cost estimate.

Task [19] Develop Algorithms for TCWS control of primary, secondary, & guiding

Description

The Telescope Control Wavefront Sensor (TCWS) will provide information required for the active control of each primary-mirror segment's tip, tilt, and piston degrees of freedom. It will also provide low bandwidth information about the primary mirror as a whole, position and orientation of the secondary mirror, and the telescope guiding. We expect that a TCWS will be located at each instrument or each focus.

Objectives

The equations describing all the optical consequences of these degrees of freedom will be derived. The interaction of the degrees of freedom and the expected bandwidths for their control will be described. A baseline control algorithm and process will be created. The possible interaction of this control with the adaptive optics control system will be studied.

Inputs

Telescope optical design

Impact on Other Tasks

Possible impact on the design of the TCWS.

Schedule

This will begin once the telescope optical design is selected and be completed after the requirements for the TCWS have been defined.

Status

As planned, this task is yet to begin.

Progress this Quarter

None

Plan for Future

Toward the end of the second quarter we will describe analytically the optical consequences of errors in all six degrees of freedom of the primary, secondary and tertiary. The telescope error budget (Task 2) will be used to set tolerances on all these degrees of freedom, as well as the required control bandwidths. Requirements will be derived for the Telescope Wavefront Sensor measurements for global control.

Task [20] Design the Telescope Structure

Description

We will produce a conceptual design of the telescope that satisfies the constraints of primary mirror and final f-ratio. The location of foci, size of science instruments, support of segments, handling of segments, support and handling of the secondary, rapid exchange of the secondary, cleaning of the mirrors, repair of key active components including replacement of actuators will also be considered in the design. Methods for periodically CO_2 cleaning the mirror will be described. A method for aligning the segments in all 6 degrees of freedom will be addressed.

Objectives

Produce a design that is compatible with all the physical and geometric constraints. The stiffness and natural frequencies will be determined, particularly the lowest modes that influence image location and quality. The possible effects of wind loads will be included in the design choices. The design will be compatible with plausible drive, bearing, and encoder systems. The support and exchange of secondary mirrors will be described.

Progress this Quarter

Steve Medwadowski has been working on several design concepts, concentrating on the upper tube (the part of the structure that connects the secondary mirror to the primary). He has analyzed 7 different design concepts, each with certain strengths and weaknesses. The key goals are to provide a lightweight, stiff support for the secondary, have a high natural frequency, and minimize the blockage of the primary mirror. Unfortunately, at this time these requirements seem to be jointly unachievable.

Steve has found several design concepts that provide a relatively lightweight structure (<60 tons) and has relatively high natural frequency (~4Hz). Unfortunately, these concepts (stiffened tripod and quadrupod) are likely to have significant blockage of the primary (5-10%).

His draft report lists various properties of these designs (report not reproduced here). We include the figures for each of the seven designs, showing the geometry and showing the motion of the lowest natural frequency. Shown below is a summary of the performance.

Summary of performance of models

Model	**light obstruction**	**mass**	**frequency**
	m^2	tons	Hz
S1	3.7	151	4.05
S2	3.7	141	2.75
S3	4.9	161	4.00
Q1	60.3	32.4	1.43
Q2	71.3	50.8	4.02
T1	45.2	24.0	1.30
T2	54.0	36.5	4.12

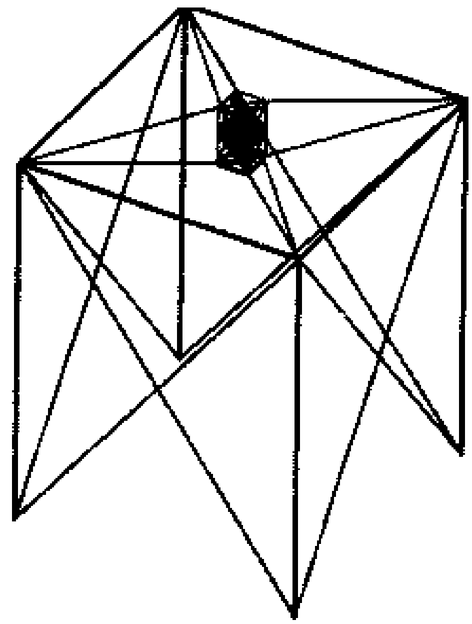


Fig. 1(a) Model S.1 - Isometric view

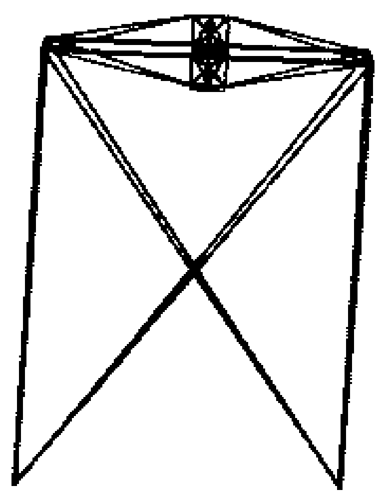


Fig. 1(b) Model S.1 - Mode shape for f_{min} = 4.05Hz

Model S1 isometric and lowest mode

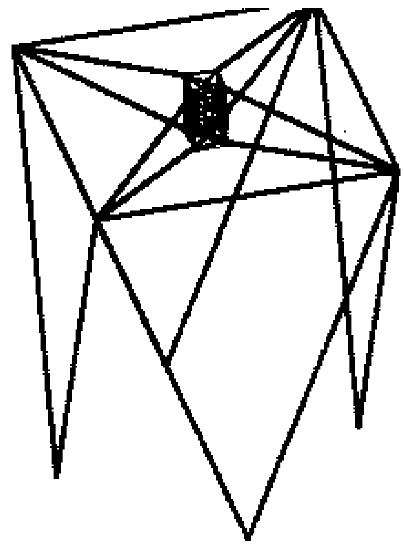


Fig. 2(a) - Model S.2 - Isometric view

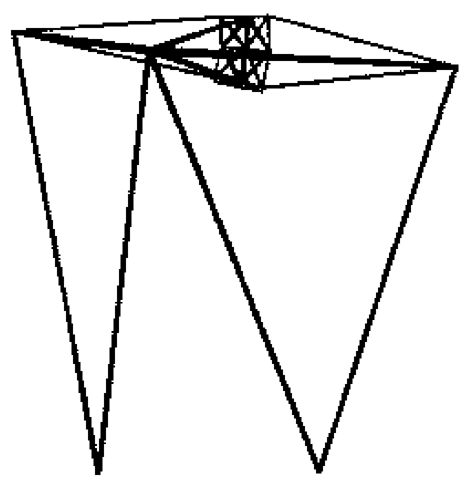


Fig. 2(b) - Model S.2 - Mode shape for f_{o} = 2.74 Hz

Model S2 isometric and lowest mode

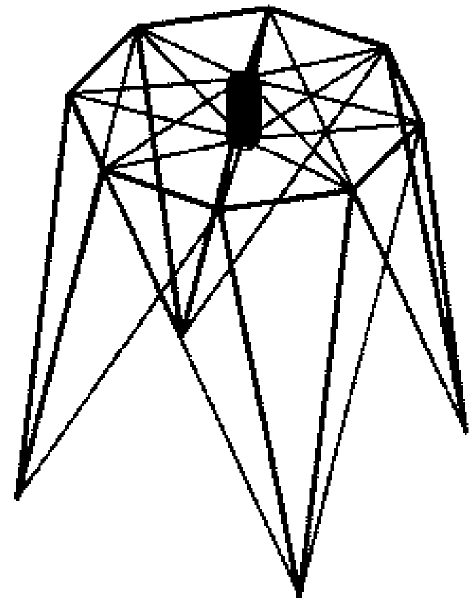


Fig. 3(a) - Model S.3 - Isometric view

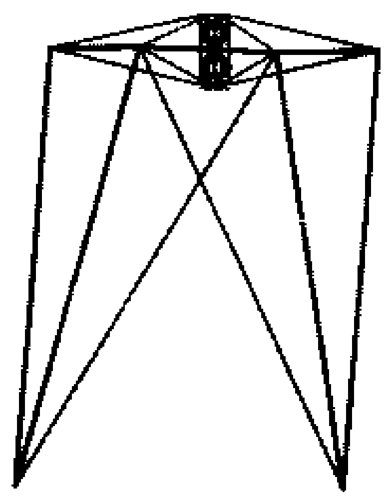


Fig. 3(b) - Model S.3 - Mode shape for f_{min} = 4.00 Hz

Model S3 isometric and lowest mode

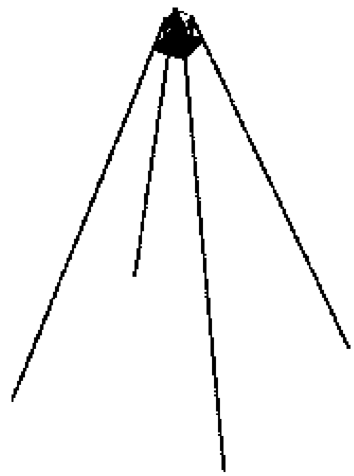


Fig. 4(a) - Model Q.1 - Isometric view

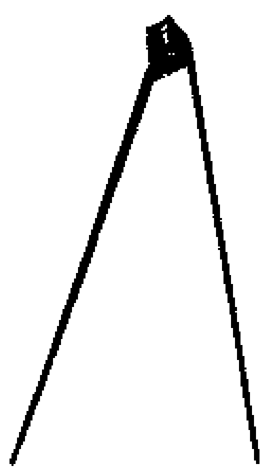


Fig. 4(b) - Model Q.1 - Mode shape for $f_{[illegible]}$ = [illegible] Hz

Model Q1 isometric and lowest mode

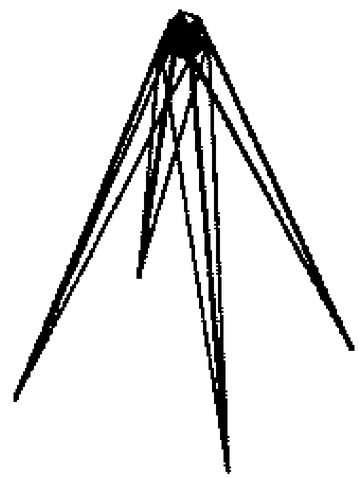


Fig. 5(a) - Model Q.2 - Isometric view

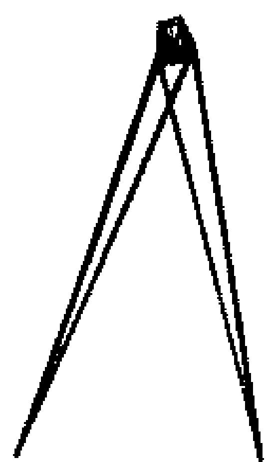


Fig. 5(b) - Model Q.2 - Mode shape for f[illegible] = [illegible] Hz

Model Q2 isometric and lowest mode

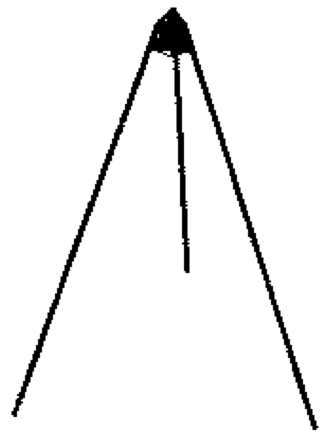


Fig. 6(a) - Model T.1 Isometric view

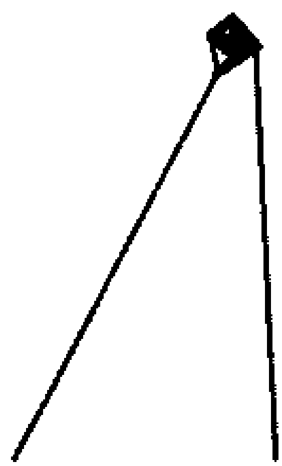


Fig. 6(b) - Model T.1 - Mode shape for $f_{[illegible]}$ = 1.30 Hz

Model T1 isometric and lowest mode

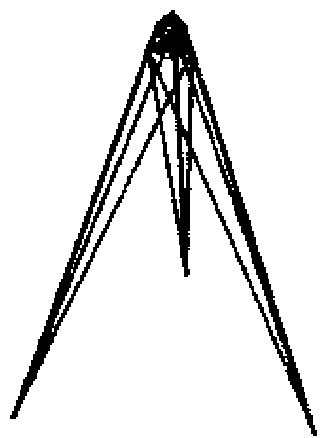


Fig. 7(a) - Model T2- Isometric view

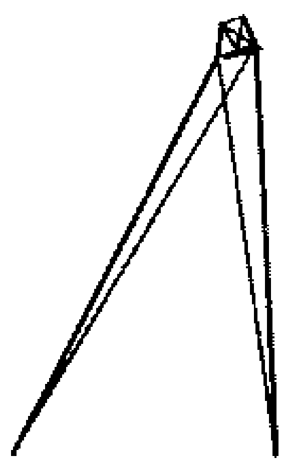


Fig. 7(b) - Model T2   Mode shape for f_{ex} = 4.12 Hz

Model T2 isometric and lowest mode

Plan for Future

Steve will pursue ways to reduce the blockage of the most efficient designs. He will look at the capabilities of lightweight trusses to do this. Complications in these designs also come from the fact that they have prestressing members. These are currently envisaged as tensioned cables to reduce their blockage of the primary. Unfortunately, these cables tend to have relatively low natural frequencies, and by their pretensioning they preload the trusses. This in turn lowers the natural frequencies of the trusses. Steve will explore these issues more quantitatively and also try to determine how important these relatively low member natural frequencies are. To first order they have no effect on the image quality.

As our knowledge about the strength and nature of the likely wind loads increases, Steve will check his designs against this disturbance in a quantitative way.

The rest of the telescope structure (mirror cell, elevation structure, azimuth structure, Nasmyth platforms) have only been sketched out. Steve will study these elements as well, and come up with a first order design for these, hopefully matched to the optimum top structure. A key issue in this integrated design is the location of the elevation axis.

The location of the elevation axis has profound structural implications. It also strongly drives the dome size. The table below shows the minimum dome size for each of the upper tube designs and two plausible elevation axis locations.

Location of Elevation axis	**Dome radius (m)** S1	**S2**	**S3**	**Q1,Q2,T1,T2**
4 m in front of primary	47.0	49	45	39.5
6 m behind primary	56.3	56.3	54.3	49.5

When we have agreed on the segment geometry, the details of the connection between the segments and the support can be detailed and the segment handling strategy worked out.

Task [21] Generate strawman designs of the bearings, drives, encoders

Description

A conceptual design of the telescope elevation and azimuth bearings, the elevation and azimuth drives, and the elevation and azimuth encoders will be generated. Attention will be given to meeting the requirements, and providing a cost effective design. Design alternates will also be given, so options are understood.

Objectives

We will develop suitable designs for all 6 systems and describe their performance. The influence of wind will be given. Alternative designs will be sketched, to provide a start for a more detailed evaluation later in the project.

Inputs

The telescope structure will define the design requirements.

Status

Progress this Quarter

We had a meeting with Vertex / RSI and discussed in some detail possible options for bearings, drives and encoders. They generally supported the use of hydrostatic bearings, gear drives, and optical strip encoders. We have very recently received from them a proposal to carry out conceptual design work and we are studying it.

Plan for Future

Negotiate with Vertex / RSI for a conceptual design study. A contract will be in place in December.

Task [22] Identify the candidate AO modes and define requirements for each mode

Description
Based on the science requirements and potential technologies, systematically identify a set of candidate AO modes. Define the system-level requirements for each mode.

Progress
In order to reduce complexity and cost risk, astronomical observations with CELT will be made utilizing a discrete number of 'observing modes' that are defined according to the unique requirements of a particular class of observations. In CELT Report #4, "Design Considerations for CELT Adaptive Optics", Dekany et. al. proposed the delineation of these observing modes based primarily upon the wavelength of the observation. This structure is a natural one within which to consider the design of adaptive optics capabilities, because nearly all of the scaling laws that drive adaptive optics are strong functions of the observing wavelength.

The following table summarizes the baseline adaptive optics observing modes described in Report #4, and updated with the results of discussions held during a multiconjugate adaptive optics workshop, held on 11/21/00 at UC Santa Cruz.

SL Mode
A discussion of the SL mode of observation was held during a visit by Gary Chanan to Caltech on 11/14/00, in coordination with Conceptual Plan Tasks #12, #13, and #15. Chanan described his progress on development of a simulation for the primary mirror induced wavefront error based upon active control system (ACS) edge sensor error propagation based upon the CELT geometry. Chanan planned to further incorporate the error propagation due to Shack-Hartman wavefront sensing errors once a tool was available to estimate wavefront tilt error based upon quad-cell centroid calculation. Dekany provided such a tool to Chanan on 11/16/00.

AO Mode	Number of High-Bandwidth Actuators	Number of Laser Guide Stars	Number of Natural Guide Stars	Number of High-bandwidth Deformable Mirrors	Role of Adaptive Secondary Mirror
Seeing limited (SL)	0	0	1	0	Low bandwidth
Single conjugate (SCAO)	~ 1,000	0	1	1	Potentially the only high bandwidth mirror
Multiconjugate (MCAO)	~7,000 – 10,000	3	1, likely 3	3	Potentially one of the high bandwidth mirrors (or used for stroke offloading)
Extreme (EAO)	> 40,000	Possible, but requires very high laser powers	1	1	Likely stroke offloading only

Table 1. Summary of AO observing modes, as expanded from CELT Report #4.

SCAO Mode

Work on the SCAO observing mode has been confined to the development of the SCAO error budget developed for Task #23 below.

MCAO Mode

A multiconjugate adaptive optics meeting was help during the Center for Adaptive Optics (CfAO) retreat on 11/7/00 and a more formal workshop was held on 11/21/00 also at UC Santa Cruz. The focus of this meeting was to evaluate the state of MCAO simulation tools, as well as brainstorm on planned laboratory and sky tests of the MCAO principal. While no specific conclusions where drawn from the workshop, the meeting served to bring the large CELT MCAO interest community up to date and is expected to lead to further collaboration for these experiments.

EAO Mode

No specific progress has been on the definition of EAO mode beyond that contained in CELT Report #4.

Future activities

During the remainder of the Conceptual Design Phase, the primary product of this task will be the development of functional requirements for each of these conceptual modes of observation. Writing these draft documents will rely, however, on certain guidance to be provided by the Science Working Group (SWG) as well as certain results from adaptive optics imaging simulations that are either currently underway (by Miska Le Louarn and others) or those that will require additional software development to address. Specifically, the following, non-exhaustive, functional design requirements will require external input:

- The maximum allowable wavefront error after adaptive correction
    - The metrics by which these standards are to be described (global wavefront rms, wavefront error as function of Zernike mode number, encircled or ensquared energy fraction, etc.)
- The uniformity of adaptive correction across the science field of regard.
    - The metrics by which these standards are to be described (wavefront error stability as a function of space and time, allowable degradation in minimum wavefront error, etc.)
- The minimum fraction of the sky and fraction of time (reliability) for which each observing mode must be usable at a specific level of wavefront error
- The number and type of guide stars and deformable mirrors required to meet the science goals

In order to continue progress on this task, therefore, increased communication between the SWG and AOWG is required.

Task [23] Develop first order error budgets for adaptive optics (AO) modes

Description

Enumerate, evaluate, and balance error budget terms for the wavefront control performance of CELT. This includes participation in Task 1 error budgets for the entire observatory. Describe error budgets in terms traceable to component-level specification (i.e. rms nm of wavefront error).

Progress this Quarter

SCAO Mode

The implementation of the SCAO observing mode for CELT closely resembles that already achieved on existing astronomical systems. Using one natural guide star to control a single deformable mirror, the conceptual SCAO system design can benefit from the extrapolation of existing error budget design tools that have been developed for the Palomar, Lick, and Keck adaptive optics systems. The unique elements of this effort, however, are the extrapolation to the longer wavelength regime (3.5-20 μm) and fainter guide stars where SCAO is expected to operate. Thus the tradeoffs between guide star exposure time, correction bandwidth, and wavefront sensing noise, for example, enters into a somewhat new regime.

At this point, conversion of existing spreadsheet-based error budget models developed for existing AO system to apply to the SCAO mode has begun (one element of this delivered for Task #15, as described above).

Other Modes

No specific progress on error budgets for the other observing modes (SL, MCAO, and EAO) has been undertaken, although the tools used for the SCAO error budget development are required for and will be directly applicable to the budget development for these other modes. Beyond the SCAO framework, however, each remaining mode will require further refinement of new physical sources of wavefront sensing or correction error (i.e., LGS spot elongation impacting wavefront measurement error in the MCAO capability).

Plan for Future

During the remainder of the Conceptual Design Phase, the spreadsheet-based formalism for the tradeoff between wavefront error sources will be expanded to include the necessary physics for a thorough description of the wavefront error sources and their dependence on first order design trades.

Several terms of MCAO error budget, in particular, will be derived only from simulation work, pending the results of planned tomography experiments. These models will be updated based upon the latest model and experiment results, and research notes in the form of memoranda will be issued to describe changes to the AO error budgets throughout the course of the CELT Conceptual and Preliminary Design phases.

Task [24] Develop conceptual AO system optical designs for each AO mode

Description

Develop a conceptual optical design for each AO mode for CELT.

Objectives

Identify key optical technology drivers, as well as any drivers in the telescope structural or configurational design (i.e., number or type of foci and secondary mirrors). Identify potential vendors and/or partners. Evaluate the state-of-the-art of AO component fabrication. Estimate the scope of any technology development programs necessary to realize the conceptual designs and estimate its cost. Provide alternatives for different cost points and describe the technical tradeoffs between these alternatives in terms of error budgets.

Progress

Richard Dekany and, under contract, Aden Meinel have conducted initial investigation of the optical designs for CELT SCAO and MCAO. A report summarizing his conceptual work is under preparation. In addition Dekany and Brian Bauman have undertaken an investigation of the first order properties of an MCAO system on a 30 meter diameter telescope in order to define the trade space available for further investigation.

In conjunction with the structural concept development of Conceptual Design Task #20, Meinel has considered the impact of several design trades on the telescope structure and to the AO capabilities. In particular, he identified several structural drivers of the adaptive optics system:

- The location of the altitude axis of the telescope, relative to the primary mirror cell
- The existence of an adaptive secondary mirror
- The existence of a forward-Cassegrain focus position
- The existence of a large field de-rotator

Altitude axis location

One of the drivers of the MCAO system in particular is the physical constraint on the size and separation of the adaptive mirrors in the multiconjugate relay. Meinel suggested that locating the altitude axis below the primary mirror (and sufficiently below to not interfere with the primary mirror support structure) could provide a large, contiguous area for both potential AO relays and the large instrumentation that CELT will require (see the Quarterly Report of the Instrument Working Group (IWG)).

The merits of this proposal relative to a more traditional optical telescope Nasmyth focus platform were discussed at several meetings, including one between Dekany and Woody which occurred at Owens Valley Radio Observatory (OVRO) on 9/29/00 and another between Nelson, Medwadowski, Mast, Woody, and Dekany at UC Santa Cruz on 10/10/00. The tentative result of a complex discussion that included the expected high cost driver of dome diameter, led this group to conclude that the preferred location for the altitude axis was above the primary mirror, resulting in the need for one Nasmyth platform on either side of the telescope structure.

Existence of an adaptive secondary mirror and forward-Cassegrain focus

The question whether to include an adaptive secondary mirror in the conceptual design of CELT rests upon the scientific driver of minimizing both the total thermal background and maximizing the stability of the thermal background, for mid-infrared observations. The optimum applicable SCAO configuration would consist of only the primary mirror, and an adaptive secondary mirror, which would perform all AO correction of the wavefront, followed by a cold dewar window located at a forward-Cassegrain focus. Both the adaptive secondary and the forward-Cassegrain focus location have implications on the telescope structure by driving the mass that must be supported by the secondary supports and the telescope bearings respectively. In addition, several technological constraints for the development of adaptive secondary mirrors apply.

The largest high-bandwidth mirror fabricated to date is the 60 cm diameter secondary mirror for the Monolithic Mirror Telescope (MMT) on Mt. Hopkins in Southern Arizona. In order to satisfy the baseline F/15 desire for Nasmyth focus, the required size of the CELT secondary mirror is approximately 3.6 meters diameter, well beyond the likely extension of the MMT technology.

Assuming that an adaptive secondary mirror of 1.5 meter diameter is feasible in the time scale of CELT construction, and maintaining F/15, a forward-Cassegrain focus is required, residing approximately 20 meters above the primary mirrors. The volume available for instrumentation at this forward-Cass has been calculated by Meinel to be a cylinder of diameter ~ 1.8 meters and height ~ 6 meters, with the envelope set by the desire to not contribute to the obscuration of the primary mirror. Meinel has suggested that all SCAO instrumentation could exploit this focus location, being serviced by an external lift while the telescope was pointed at the horizon (a feature directly implemented if the altitude axis was placed behind the primary mirror).

The determination of the need for either or both of the adaptive secondary mirror and forward-Cass focus will depend in the coming months upon the deliberations of the SWG, further structural analysis of the secondary mirror support mechanism, evaluation of the costs associated with larger than state-of-the-art adaptive mirrors, and continued consultation with the IWG.

Should adaptive secondary preliminary design be required, it is expected that at least one visit to the Osservatorio d'Arcetri in Firenze, Italy for consultations on their development of the adaptive secondary mirrors for the Large Binocular Telescope (LBT) will be needed.

Field de-rotator

Meinel has also considered the size of the field de-rotator that would be necessary to compensate for the field rotation with time induced by the altitude-azimuth geometry of the CELT baseline. Assuming a 4 arcminute diameter field of view (FOV), and a 450 meter telescope focal length, a traditional 'K-mirror' field de-rotator, using a 65 degree incidence would consist of 3 approximately 1 meter diameter mirrors that would span a cylindrical volume of about 2 meter diameter x 4 meter length. The challenge of maintaining the mirror figure within the de-rotator seem sufficient to seriously consider the impact of requiring all instrumentation to rotate about their optical axis (at least within a given focus location, if there are several).

This topic has not been specifically addressed by the AOWG and IWG in joint discussion, so the relative challenge of the two approaches is unknown. This issue will be taken up by the IWG in future discussions.

Compact triad MCAO

Brian Bauman, of Lawrence Livermore National Laboratory (LLNL), and Richard Dekany have also undertaken an analysis of the first order optical properties of MCAO designs in connection with extremely large telescopes. Of particular interest has been the investigation of MCAO concepts that do not require large departures from the existing state-of-the-art in deformable mirror (DM) technology and also maximize optical throughput by minimizing the total number of surfaces encounter by the science path.

Perhaps the most straightforward implementation of an MCAO system is the use of multiple deformable mirrors in the same optical space. Because this configuration often leads to the placement of DMs in close proximity, we shall refer to this arrangement as a compact triad. Because a two-mirror telescope forms conjugates of different heights in the atmosphere behind it's focus, each of these configurations requires the use of at least one additional optic to form a real corrected image. Using the well-known (but not widely known) y,y-bar layout technique, Bauman investigated the use of a compact triad in a collimated optical space.

A use of multiple DMs in a collimated space has several practical advantages. The scale registration of a DM relative to a wavefront sensor is independent of small errors in mirror positioning when using collimated light. In addition, it is often possible to arrange simple optical alignment and monitoring systems, based upon retro-reflection techniques, using a collimated space. For the placement of three deformable mirrors conjugate to altitudes of 0km, 5km, and 10km above the primary mirror, Bauman derives the deformable mirror diameters and incidence angles shown in Figure 1.

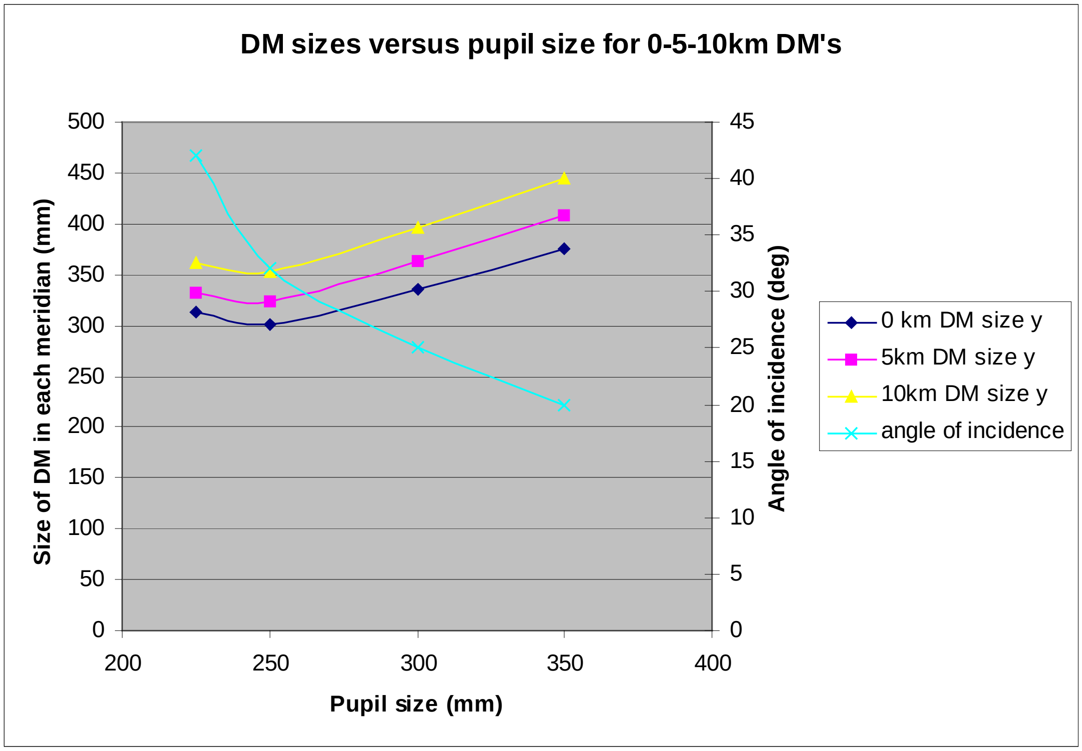


Figure 1. Deformable mirror diameter for three conjugate locations in a collimated space. The 0 km conjugated mirror is the smallest diameter while the 10 km conjugated mirror must increase in diameter to accept a field angle (in this case) of 2 arcmin diameter. For small pupil sizes, the packaging of three mirrors in a small space leads to the increasing mirror diameter. (The placement of three DMs in a diverging beam leads to a similar curve, but all mirror diameters can be made equal.)

From this figure, we conclude that there exists a feasible MCAO design based upon a very slight improvement over today's state-of-the-art 300 mm diameter flat deformable mirror technology.

Future Activities

Meinel is currently working on a report of the three MCAO optical design considered for CELT, the Offner relay, the compact triad, and the cross-beam configuration. Dekany and Bauman are additionally expanding upon some of these concepts. Because the requirements on the stroke of each deformable mirror in an MCAO relay may be different, Dekany and Bauman intend to continue the development of alternative relay designs that incorporate stroke information based upon discussions with Dr. Mark Ealey of Xinetics, Inc. The goal of this near-term activity is to put the feasibility of at least one MCAO optical design firmly in place to allow continued development and costing of the CELT observatory concept.

Similarly the optical design of the SCAO system will be further developed and documented according the decisions reached by the SWG, the IWG, and the Telescope Working Group (TWG).

A conceptual optical design for the EAO capability is expected to consist of a single conjugate AO system with extreme pupil demagnification, in order to facilitate the use of extremely high actuator count microelectromechanical system (MEMS) deformable mirrors. There is current activity on the design, fabrication, and testing of MEMS devices underway at LLNL, Berkeley Sensor and Actuator Center (BSAC) and Jet Propulsion Laboratory (JPL).

Gary Chanan and his group are conducting the conceptual optical design for a telescope wavefront sensor under Task #15, though further analysis of the controls problem may lead to clearer integration of this sensor into the adaptive optics systems.

Related Activities

Palomar Multi-conjugate Testbed Planning

On 10/4/00, Richard Dekany made a presentation to an ad hoc Palomar Review Committee formed by the Palomar Director, Prof. Richard Ellis to make recommendations on, among other topics, the future research direction for Palomar Observatory. Dekany advocated the establishment of a decade-long testbed development for MCAO in three stages. The result of the Palomar Multi-conjugate AO (PALMAO) program would be the demonstration of visible multi-conjugate AO on the 5 meter diameter Hale Telescope as a technology demonstration for CELT MCAO. Dekany included in his presentation a request for funding to carry forward the preliminary design of the first phase of this testbed in the period of Dec 2000 – July 2001.

A report from the Review Committee, including a list of recommendations to the Director on the future of such an AO testbed, is expected by January 2001.

NSF ATI Proposal

In support of enabling tomographic wavefront sensing experiments using the Palomar AO (PALAO) system, a proposal to the National Science Foundation (NSF) Advanced Technologies and Instrumentation (ATI) program, Richard Dekany, PI, was submitted on 8/31/00. The request of NSF is to fund the establishment, as part of the first phase of the PALM testbed development, of a four-channel wavefront sensing system for use on multiple guide stars (both natural and synthetic).

MCAO modeling

The conceptual design of multi-conjugate adaptive optics (MCAO) for CELT is currently limited by the scarcity of adequate tools needed to investigate an extremely rich design trade space. Many of the key questions pertaining to CELT MCAO can in principle be addressed through computer modeling and simulation, although the practical challenge imposed by today's computer hardware is significant.

The development of MCAO modeling tools was not included in the CELT Conceptual Design Plan (CELT Report #9) because it was believed that this activity was being supported within the Center for Adaptive Optics (CfAO). In fact, CfAO postdoc Miska Le Louarn has been writing such simulations and presented his work to a workshop on MCAO in November 2000. Miska's work to date, while encouraging, has not sufficiently addressed the many trade issues of CELT MCAO.

Based upon this, and the progress of the simulation effort within the Gemini AO group (Ellerbroek and Rigout), additional effort in MCAO modeling, beyond that currently supported by CfAO, is needed to complete Design Tasks #23-25. Dekany is undertaking a review of the existing simulation codes and will make recommendations in support of both CELT and PALMAO development by 22 December 2000.

Other significant events of the Quarter include:

- Richard Dekany talked on "CELT AO Concepts" at the Center for Adaptive Optics Summer School on 7/14/00. Published proceedings are planned.
- Ed Kibblewhite of University of Chicago gave a seminar at Caltech on 8/14/00 on two topics: the development of high power sum frequency solid-state sodium lasers and a concept for a Schmidt-telescope-like ELT. The very wide field of view of the Schmidt telescope could allow an entirely new way of conducting astronomical science with several groups sharing a seeing limited focal plane that would be several to many meters in diameter.
- Roberto Ragazzoni of Astronomical Observatory of Padova visited UC San Diego as a guest of Profs. Tytler and Quirrenbach. An informal seminar was held with CELT AOWG members on 9/18/00 to discuss innovative wavefront sensing schemes including pyramid sensors and layer-oriented sensing schemes.
- Bi-weekly Adaptive Optics Group meetings were initiated at Caltech on 9/22/00, bringing together adaptive optics users, engineers, and students to discuss AO science and technology issues. Videoconferencing may be possible to open these meetings to virtual attendance (Dekany will issue a memo on the feasibility of videoconferencing all AO Group meetings).
- A teleconference to discuss laser guide star return flux modeling was held on 10/1/00, led by Dee Pennington and Celine d'Orgeville.
- During a laser guide star observing run in October 2000, the Lick AO team, led by Don Gavel, achieved over 50% Strehl ratio (K-band) for observations made when guiding upon a sodium laser beacon. This is thought to be the highest long-exposure Strehl ratio ever achieved with an astronomical laser guide star system.
- AOWG Chair Richard Dekany accepted a fulltime position at California Institute of Technology effective 11/13/00.

Task [25] Prepare for Conceptual Design Review

Description

All results of this phase will be collected and presented at a Conceptual Design Review (CoDR). At this review, the conceptual design of the telescope, AO, and instrument subsystems should be presented, as well as an update on site selection. A key component of the review will be to understand the level of effort necessary for the Preliminary Design phase, which will address many details not addressed by the Conceptual Design phase.

Inputs

All results from this phase

Schedule

This task will not begin until close to the end of this phase and will not be completed until after the Conceptual Design Review.

Progress this Quarter

None

Plan for Future

This work will be begun in the last quarter

Task [26] Write the Preliminary Design development plan.

Description

We wish to develop the plan for the next phase of work, the preliminary design phase. This will consist of a description of the key tasks, the method for carrying them out, the likely budget and the schedule. Tasks will include more detailed descriptions than the conceptual design, resolution of issued raised in the conceptual design review, progress on key issues that were not undertaken in the conceptual design.

Schedule

This task will not begin until the final month of this phase.

Task [27] Support the CELT Working Groups

Description

The CELT working groups need some funds to operate; travel to meetings, small studies, etc. This task provides those funds.

Other Participants

CELT working groups, including Steering Committee, Telescope, Science, Instruments, Adaptive optics, Site

Progress this Quarter

Working group activities are generally being reported separately. The Telescope and AO progress is included in this document

Task [28] Manage the Conceptual Design phase program

Description

The management of the phase 1 Development program will be begin with the definition of detailed tasks, schedules and milestones. These schedules and milestones will be regularly tracked during the program and updated in response to changing requirements and to changes in the cost-risk assessments. We will also define cost codes corresponding to all aspects of the program and track them against the approved budgets. When required, consultants and suppliers will be contracted for portions of the program. Budget and schedule summaries will be produced quarterly.

Objectives

Manage the conceptual design to a successful conclusion. This means a sound design will be developed, budget will be met, and schedule will be met. Also, preparation for the next phase will be completed.

Progress this Quarter

We currently have three contracts with consultants for work on CELT. Paragon Engineering (Steve Gunnels) has been contracted to carry out the conceptual study of the primary mirror segment support. The Pilot Group (Alan Schier) was contracted to carry out the conceptual study of the primary mirror actuators, and Steve Medwadowski was contracted to carry out a study of the telescope structure. We expect these studies to be completed in the early part of 2001.

Plan for Future

We are planning to contract at least three additional studies in the next few months; a conceptual study of bearing, encoders and drives; a conceptual study of segment displacement sensors; and a conceptual study of one particular type of primary mirror actuator. These contracts will likely be let by the end of the year or early next year.

Task [29] Manage the CELT Website

Description

The CELT website is both a description of the project to the world and an internal communications tool.

Objectives

We will upgrade and maintain the CELT website, so that it announces all project activities, provides an archive for reports describing the results of all tasks, and educates the public about the nature and status of the project.

Status

The CELT web pages are hosted at www.ucolick.org/~CELT
and there are links to the site at
The Caltech astronomy site www.astro.caltech.edu/
and a major existing telescopes site www.seds.org/billa/bigeyes.html

Progress this Quarter

We have completely revised the organization and appearance of the website. It now includes the general categories of Institutions, Working Groups, Individuals, Calendar, Reports and Notes, and Presentations; as well as some artist concept renderings of the telescope. The Reports and Notes category contain the full text of CELT reports and technical notes. The Presentations category contains, when available, presentations made at internal meetings.

This site is providing both an internal record and a description to the world of the CELT personnel, activities, and progress.

Plan for Future

The website will be updated regularly as additional reports, technical notes, and presentations are created. If resources are available, we will add a section giving the scientific and technical motivation for CELT that is specifically directed to the public at large.

Task [30] Contingency management

Status

$250K is being held as contingency

Progress this Quarter

The contingency has not changed, but it seems likely that we will need to allocate some additional resources for actuator work and for telescope design work.