California Extremely Large Telescope
Implementation Plan for a Thirty-Meter Telescope

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Chapter 1. Introduction

For many centuries exploration of the world by courageous discoverers profoundly influenced the development of civilization. The discovery of new lands and new societies brought pivotal changes to our world. Whether it was the discoveries of Polynesian adventurers crossing the Pacific Ocean or European explorers in the New World, the desire to explore and understand the unknown is a fundamental trait of the human race. In many respects the scientists of the 20th century were the modern equivalent of these explorers. Venturing into the microscopic world of the atom and the vast reaches of the universe, they made discoveries that had as profound an impact on the development of civilization as those of the earlier explorers of our planet.

Entering the 21st century, we stand on the threshold of dramatic astronomical explorations. The universe has been a source of interest, inspiration, and wonderment since the earliest times. Today newspapers and magazines are filled with exciting new discoveries of astronomy because they appeal to something fundamental in human nature. People are eager to know about the universe in which we live, how it began and how it evolved to its present state; and to understand our place in it. We want to know:

- Why is the space of the universe filled with galaxies?
- Why are galaxies filled with stars?
- Why are stars surrounded by planets?
- Is the existence of life an extremely rare event or common in the universe?

We are beginning to answer some of these questions with existing telescopes on the ground and in space. The next generation of astronomical instruments will dramatically improve our ability to find answers to these questions that have intrigued human beings for thousands of years.

Scientists at the University of California and the California Institute of Technology propose to design, build, and operate a 30-meter telescope observatory that will be an extraordinarily powerful tool for exploring the universe. It will see farther into space and farther back in time than any instruments currently in use. It will give us unprecedented access to exquisite details of physical processes on both small and large scales and over most of the age of the universe.

- We expect to see galaxies at their birth, when the first stars formed in the universe and started the processes that resulted in the world on which we live.
- We expect to further understand the evolution of galaxies from birth to the present.
- We expect to have detailed views of stars and solar systems in the process of formation.
- We expect to observe directly planets in orbits around other stars, planets that may be the abodes of life.

All this and much more will be possible because of the enormous light-gathering power and extremely high spatial resolution of a 30-meter telescope. The same scientists who conceived of and very successfully led the creation of the two largest telescopes in the world at the Keck Observatory are now prepared and eager to lead this exciting new venture. We are confident it will succeed, and the discoveries that flow from this magnificent new instrument will advance our understanding of the universe to a profound new level.

In the first volume of this proposal, we present the scientific case for a 30-m telescope and describe the reference design and technical issues related to the design. In this second volume (The Implementation Plan) we discuss organizational aspects of CELT including management, schedule, budget, and key technology development. This is called the CELT Development Project (CDP).

Chapter 2. Scope of Implementation Plan

This plan covers all of the activities required to define, develop, and operate an observatory that contains the California Extremely Large Telescope (CELT) and a complement of dedicated science instruments. It includes a description of the ownership entity and its relationship to the implementing elements of observatory. It describes the approach to be taken and products delivered during each of the future phases in the life of the observatory. Those phases are:

Phase 2 - Project Definition
Phase 3 - Development
Phase 4 - Operations

Phase 1, the Conceptual Design, is complete. Volumes 1 and 2 are the products of Phase 1 and mark its completion.

The means by which the owners raise and distribute funds to the observatory activities is not included in this plan.

It is our intention that this plan constitutes the agreement between the owners and the observatory's developers and operators. We present this plan for approval by the owners.

Chapter 3. Overview of Implementation Plan

3.1 Phased Development

The CELT Observatory will be implemented in four phases. The content and timing of these phases are summarized in Table 3-1.

This four-phase implementation plan will allow the project to proceed in a low risk and efficient way before full funding is committed. It provides a period, Phase 2, for a specialized and dedicated team to refine the design concept and cost estimate, mitigate key risks, initiate the design, and refine the Phase 3 and Phase 4 implementation plan.

3.2 Owner Organization

The California Institute of Technology and the University of California (CIT/UC) will form a joint implementation partnership as coequals in all respects. These institutions will be referred to as "owners." In order to provide autonomous requirements development and design by CIT/UC and their associates, partnerships with others at the observatory ownership level will not be formed until after Phase 2, if at all. Technology development ventures will be solicited with groups that have goals in common with CELT.

CIT/UC will form a single entity called the CELT Development Corporation (CDC). A Board of Directors of the CDC will distribute funds to the CELT activities and have ultimate responsibility for the success of the CELT venture. The board of directors will have three members from each institution, including the directors of Caltech Optical Observatory and UC Observatories.

To expedite the accomplishment of the Board's responsibilities, the CDC Board will assign a single person for oversight and communication with the major project elements. This person will be appointed by the Board and will be the Chief Executive Officer of the Corporation (CEO). The CEO will represent the CDC and will work with the Observatory Development Project Manager, Project Scientist, Science Advisory Committee, and Operations Director on a regular basis. The CEO will be a member of the CDC Board, have a background in research astronomy, and be familiar with large-project management.

The owners will obtain funding for CELT from private sources. Funds will be made available to the activities (see below) according to the defined in section 3.4.

3.3 CELT Organization

The organization and reporting relationships are shown in Figure 3-1.

There will be three CELT activities that have separate funding plans and leadership.
1. Observatory Development
2. Science Oversight
3. Observatory Operations.

Table 3-1. CELT Observatory Phased Development Summary

Project Phases	Activity	Start Time	Duration (Months)	Objective - Key Tasks
Phase 1 “Conceptual Design”	Prepare Proposal	10/00	18	Establish project feasibility - Build compelling scientific justification - Complete initial design concept - Establish technical feasibility - Prepare draft of top level requirements - Prepare draft project implementation plan including detailed Phase 2 cost/activity plan - Identify key risks and mitigation approaches
	Review Proposal	4/02	3	Finalize project plan - Present project plan and design concept to owners - Owner review of proposed plan - Peer review of proposed plan - Revise plan to meet owner’s requirements - Decision to proceed
	Establish Project	7/02	~ 6	Establish project infrastructure and leadership - Establish CELT parent organization and project governance protocol - Initiate long lead Phase 2 activities (e.g. recruit critical staff, start site surveys, proceed with actuator and sensor engineering models, ...) - Appoint Science Advisory Committee - Select Project Manager - Select Project Scientist
Phase 2 “Definition”	Project Initiation	Q1/03	6	Build project team - Establish project office - Finalize Project Implementation Plan - Recruit management/technical staff - Finalize top level design requirements - Continue pre-production prototype development - Continue design trades and conceptual design - Complete Conceptual Design - Establish tentative site baseline
	Preliminary Design	Q3/03	30	Prepare final observatory construction and commissioning plan - Prepare detailed requirements - Select science instrument developers - Complete Preliminary Design - Complete pre-production prototype development - Finalize long-lead designs and initiate long-lead procurements/construction - Prepare final implementation budget - Complete technology development - Receive funding-to-complete confirmation
Phase 3 “Development”	Final Design	Q1/06	6	Complete design - Finalize site selection/commitment - Initiate long-lead procurements/construction - Complete design
	Construction	Q3/06	39	Complete component and facility construction - Construct summit and headquarters facilities - Fabricate telescope and associated components
	Commissioning	Q4/09	42	Complete assembly and commissioning of observatory - Assemble and test telescope - Install and test science instruments - Appoint operations Director - Finalize operations plan - Assemble operations staff
Phase 4 “Operations”	Operations	Q2/13	-	Initiate operations - “Delivery” of completed observatory to Director

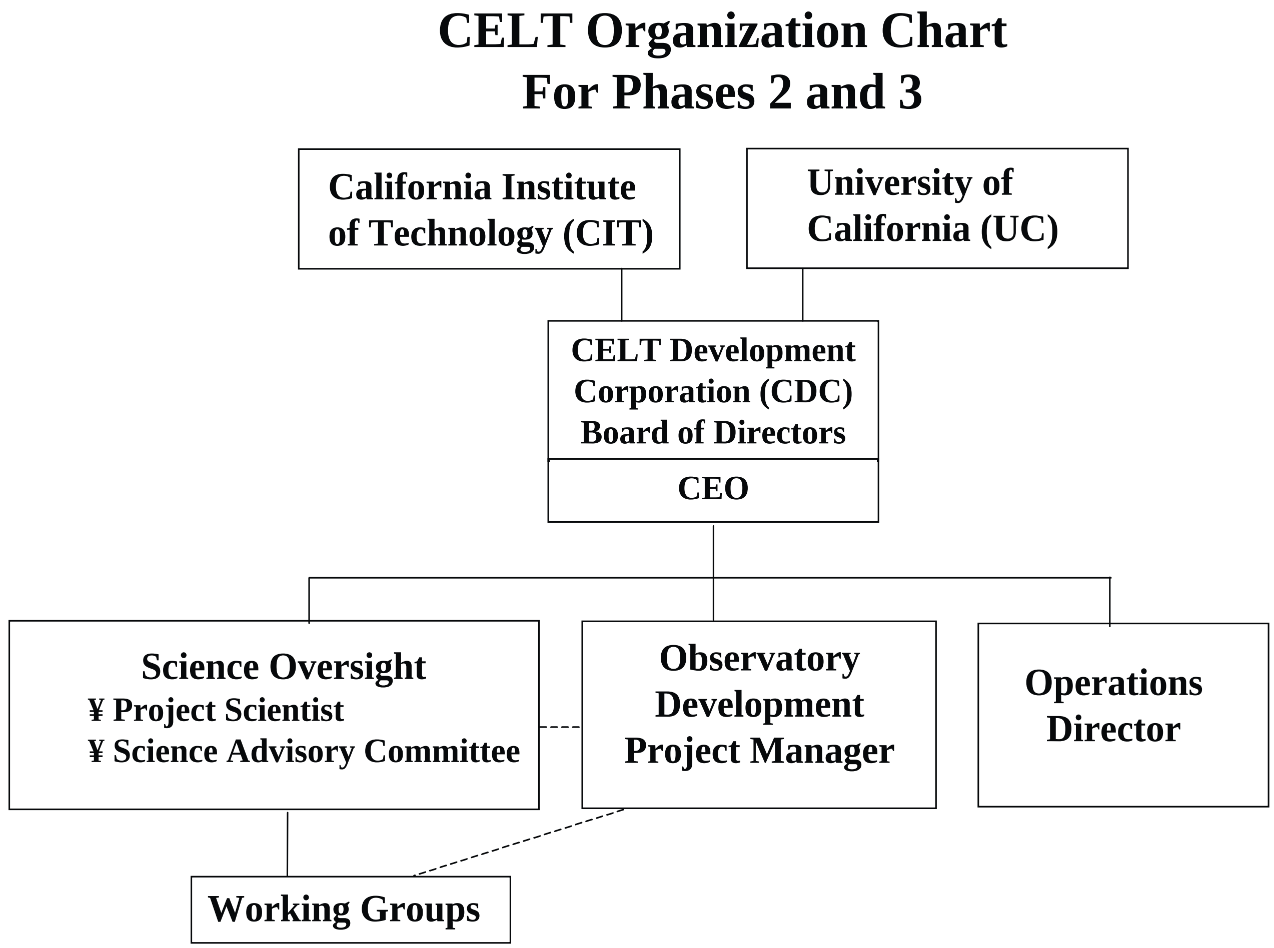

Figure 3-1. CELT Organization chart for Phases 2 and 3.

The CDC Board will delegate responsibility for these activities to leaders as follows:

1. Observatory Development - observatory Project Manager (PM) (Chapter 4)
2. Science Oversight - Science Advisory Committee (SAC) (with chairs and membership appointed by the CDC Board) and the Project Scientist (PS) (Chapter 5)
3. Observatory Operations - Operations Director (Chapter 6)

We give here the roles and responsibilities for the leaders of the three top elements.

Observatory Development Project Manager

The Project Manager will be responsible for all aspects of project operations and performance. Key tasks:

1. Prepare and maintain the project plan.
2. Concur with the SAC on Level 1 requirements
3. Execute the project according to the project plan.

4. Select, lead, and maintain the project team.
5. Communicate with the CDC regarding all project matters.
6. Make reports to the Board and the SAC on a quarterly basis.
7. Make reports to the CEO on a weekly basis.
8. Form working groups for advice on specific issues with the SAC.
9. Approve major procurements.

Project Scientist (PS)

The Project Scientist will be responsible for assuring the scientific utility of the CELT observatory. Key tasks:

1. Develop Level 1 observatory requirements and goals with the SAC. Level 1 requirements will include science instruments, adaptive optics, and all other key aspects of the observatory
2. Ensure the science requirements are being satisfied in the observatory design and construction.
3. Assist the Project Manager in dealing with day-to-day engineering and technology issues.
4. Assess the technical integrity of the design of the observatory and its implementation. The Project Scientist will have a small staff.

Science Advisory Committee (SAC)

The SAC will be responsible to the CDC for ensuring the scientific utility of the CELT observatory. They will do so by communicating the needs and concerns of the scientific community to the Project Manager and the Project Scientist to help ensure the scientific utility of the CELT observatory. Key tasks:

1. Develop the Level 1 Observatory requirements and goals with the Project Scientist.
2. Lead and coordinate the process leading to the selection of the science instruments
3. Lead and coordinate the process leading to the selection of the baseline adaptive optics systems.
4. Form working groups for advice on specific issues with the PM.
5. Advise (without budget control) the Adaptive Optics Manager and the Instruments Manager.
6. Report quarterly to the CDC Board.
7. Solicit input from the scientific community.
8. Provide a forum for input from the scientific community.

Operations Director

The Operations Director is responsible for all aspects of operations of the facility once it is successfully commissioned. The Operations Director should take the lead in ensuring the facility can be operated economically, safely, and with the highest astronomical efficiency.

1. Work with the Observatory Development Project Manager to lead the transition from commissioning to operations.
2. During Phase 3, review facility designs and procedures to ensure that the observatory can be operated in an economical and efficient manner.
3. Recruit and hire operations staff, and integrate Phase 3 staff into the operations staff where desirable and practical.
4. Beginning in the latter half of Phase 3, report quarterly to the CDC Board.
5. Participate in the Observatory commissioning, to ensure the operations staff has direct knowledge of the facility and its maintenance needs.
6. Generate an operations plan and budget, to be reviewed and approved by the CDC

7. Interact with the astronomical user community to ensure that science instruments are working as planned, and that second generation science instruments are being developed in a fashion consistent with the scientific desires of the community and with the capabilities of the Observatory.

3.4 Budget and Schedule

The Summary Budget is given in Figure 3-2. Costs are shown in real year dollars, assuming a 2.5% annual inflation rate. This budget shows the work breakdown structure (WBS) and provides the cost for each element (Level 1) as a function of time over the entire project. Phase 2 costs are shown and summed, and Phase 3 costs are shown and summed.

The estimated sustaining costs are also indicated. Minimizing the cost of operations will be a high priority during both Phase 2 and Phase 3. These costs are assumed to ramp up during the final years of construction to allow a smooth transition to operations and to allow additional early funds for the development of second generation science instruments. The distinction between operations and observatory development activities can be difficult to draw, and the sum estimate is probably more accurate than the indicated division between “operations” and “instruments and adaptive optics”.

Annual spending is also shown at the bottom and indicates the annual commitment required of the owners. A detailed budget for the observatory development is contained in Chapters 4, 5, and 6 below. Figure 3-3 shows the key milestones for the CELT development. The schedule has been constructed to proceed as quickly as practical to an operational observatory while allowing ample time for risk mitigation activities and appropriate schedule reserve.

CELT Budget Summary

(Real year $K, 2.5% inflation/yr assumed)

	Phase 2			Phase 2	Phase 3								Phase 3	Phase 2+3	Annual Budget
Cost Element\Fiscal year	**2003**	**2004**	**2005**	**Subtotal**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Subtotal**	**Total**	**2014+ ****
Observatory Development															
Project management	1364	1243	1161	3768	1444	1513	1787	2942	1924	1965	2088	1326	14988	18756	
System architecture and analysis	544	595	594	1733	812	1029	1141	703	706	739	774	440	6344	8077	
Project engineering	183	332	554	1069	661	698	733	773	818	952	897	596	6126	7195	
Site acquisition	2314	932	919	4165	6464	0	0	0	0	0	0	0	6464	10629	
Enclosure	608	1751	1401	3760	6348	16751	7566	6870	0	0	0	0	37535	41295	
Telescope mount	819	1720	2579	5118	9562	11652	11739	3616	819	0	0	0	37388	42506	
Optics	1657	1244	3191	6091	11036	17761	13203	8650	5622	0	0	0	56272	62363	
Optics passive support	543	690	451	1684	1629	1867	1900	1431	632	0	0	0	7459	9143	
Optics active control	1121	1075	924	3121	4298	5189	5333	2799	2399	1442	547	560	22567	25688	
Adaptive optics	6580	7540	7117	21237	8819	17669	31179	23898	13593	13071	11044	8171	127444	148681	
Facilities	161	417	604	1182	1369	6540	12479	5687	573	196	201	0	27043	28225	
Software and related hardware	683	1062	1628	3372	1640	1908	1656	1433	1328	1303	1321	982	11570	14943	
Observatory commissioning	0	17	18	35	105	219	1275	2707	3353	3335	3394	1746	16134	16169	
Scientific Instrumentation allocation*	2191	3671	4948	10810	6379	8036	10765	12083	13236	11054	5904	0	67457	78267	
Reserve*	2143	3019	4743	9906	15172	23111	20902	14455	7520	2609	2198	1392	87358	97264	
Subtotal Observatory Development	*20911*	*25308*	*30831*	*77051*	*75738*	*113943*	*121655*	*88047*	*52522*	*36665*	*28366*	*15213*	*532150*	*609201*	
Scientific Oversight															
SAC operations and discretionary funds	98	100	103	301	106	108	111	114	116	119	122	125	922	1223	
Sustaining Activities															
Science instruments & AO - rampup to sustaining ($15M/yr in yr 2000 dollars)								2623	5760	8463	14121	20678			21195
Operations- rampup to sustaining ($15M/yr in yr 2000$)									1920	3936	8069	16542			21195
Total Funding Required	**21009**	**25409**	**30934**	77352	**75844**	**114051**	**121766**	**90784**	**60319**	**49184**	**50679**	**52558**	615185	**692537**	**42389**

*Scientific Instrumentation is cost bounded and its reserve is internal to its budget and not in the general reserve

** Shown is the annual budget for the year 2014. This includes funding for operations and additional instruments. For 2015 and beyond we assume that the 2014 budget is inflated by 2.5 % per year.

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Figure 3-2. CELT Budget Summary

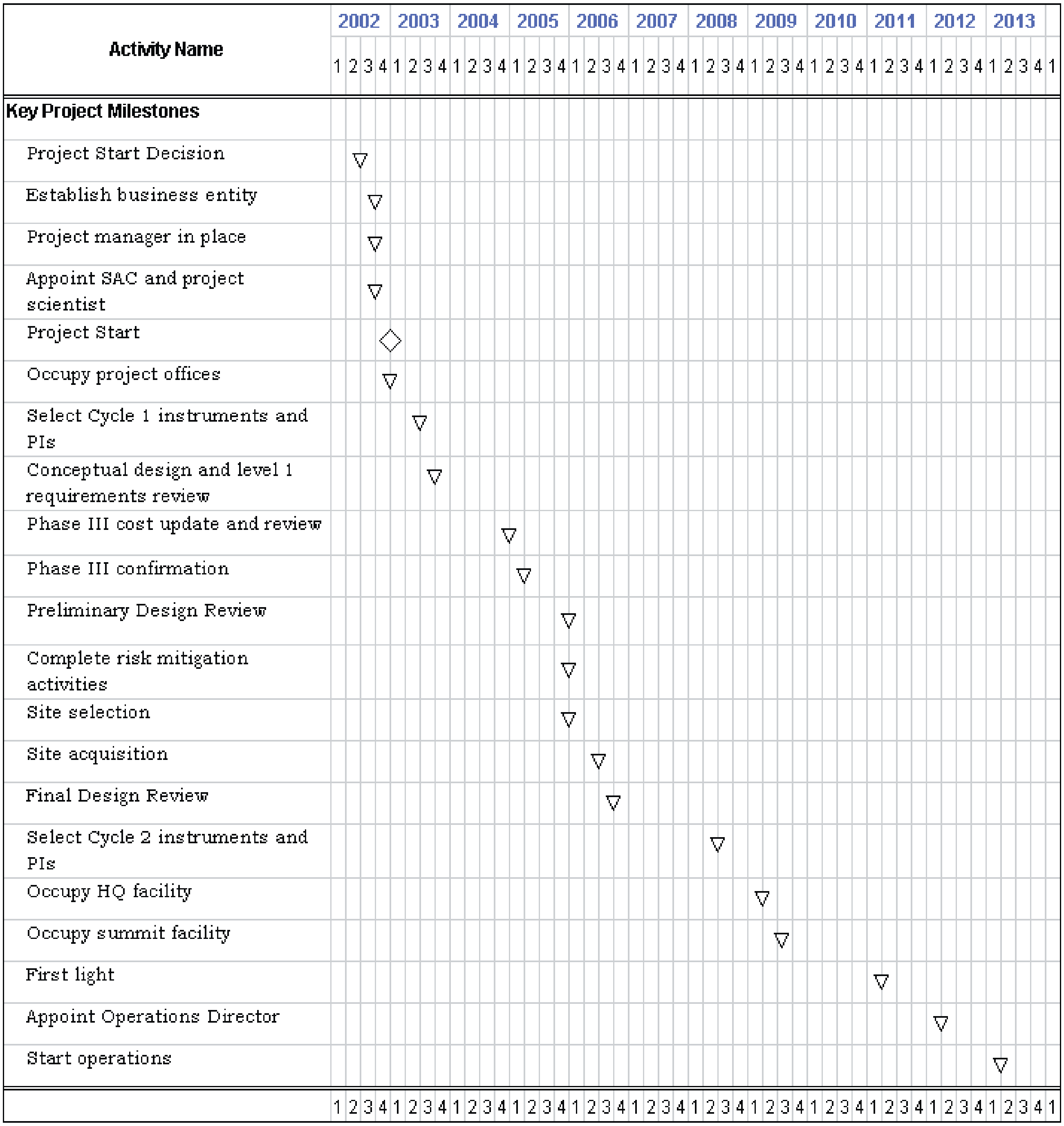

Figure 3-3. Key CELT Project Milestones.

Chapter 4. Observatory Development Plan

This Chapter describes the plan to develop the CELT Observatory. The observatory will be developed by the CELT Development Project (CDP), which will be created by the CDC for the purpose of developing and commissioning the observatory.

4.1 Scope

Observatory development will include all aspects of planning, technology development, design, construction, and testing. Its product is the delivery of a functional observatory, which meets the Level 1 requirements defined in Nelson (March 2001).

Final Level 1 requirements will be established during the first year of Phase 2. The requirements will be agreed upon by the CDP in conjunction with the CELT Science Advisory Committee (SAC) and the Project Scientist (PS).

4.2 Implementation Approach

This proposed CELT Observatory implementation approach responds to the following key assumptions, which are believed to characterize the owners' intent:

1. The development approach should leverage the experiences of the owners in a previously successful joint venture of this type, the W. M. Keck Observatory.
2. The owners will acquire funding from private sources and provide it to the development project in a timely way.
3. The owners are committed to supporting the observatory development by facilitating access to staff and facilities from their respective institutions (e.g., LLBL, LLNL, JPL). "Access" in this context means use (paid by the CDP) of staff and facilities when such use provides talent and/or capability which is not readily available commercially.

4.2.1 Development Team

The unique nature of an undertaking of this type calls for the formation of a team dedicated solely to the development of the observatory. Therefore the design and construction of the CELT observatory will be led by a small team of managers, scientists, engineers, technicians, and office staff who will be selected for their expertise in the areas relevant to observatory development. This team will coordinate the contributions from industry, academia, and government (if national labs possess expertise unavailable elsewhere) to produce an integrated CELT observatory.

The CDP team's tasks will vary widely across the observatory's constituent areas; however, in general the CDP team will

1. provide a single focal point for all matters relating to observatory development,
2. produce and maintain all requirements,
3. develop conceptual designs for all areas,
4. direct the efforts of all first tier subcontractors, and
5. lead the assembly and test of the observatory.

4.2.2 Implementation Phases

Phase 1 is assumed to be complete, and its key objectives achieved, i.e., the feasibility of the CELT has been established and a viable conceptual design is in place.

Phase 2 will culminate in a selected site, a completed preliminary design, demonstrations of feasibility for critical technology and cost areas, and a firm cost/reserve estimate to complete the project. It is important that Phase 2 be funded at ~10% of the expected total cost of the observatory development, since actual cost histories of projects at this level of technology reveal significant reduction in cost-to-complete uncertainties with this level of front-end investment. Another important benefit of a well-funded Phase 2 is that highly qualified staff can be offered stable employment for the three years of Phase 2 and a stake in a much longer assignment if they produce an attractive project plan by the end of the second phase. Key staff ownership of the cost, schedule, and performance plan is an additional benefit of this four-phase approach. Thus continuity of project staff from Phase 2 to Phase 3 is assumed in this plan. For this to be achieved, Phase 3 funding prospects need to be assured comfortably before the end of Phase 2 (around one year). A review will be held to confirm the plan for Phase 3.

Phase 3 will culminate with an operational observatory with an initial suite of science instruments.

4.2.3 Implementation Process

The baseline plan for the sub-allocation of tasks within the CDP is indicated by the summary budget presented in Section 3.0. Each cost element shown in the summary budget will be implemented according to the approach described below. Key decisions are required for each element in order to define and establish the need for a technology development plan, an engineering-model strategy, and a “make or buy” decision for design, manufacture, assembly, and testing of each cost element.

The criteria used to make these decisions are:
1. Minimize cost to achieve acceptable quality.
2. Minimize cost/schedule growth risk.
3. Minimize operations cost.
4. Utilize demonstrated expertise.
5. Limit in-house detailed design and manufacturing to those areas that cannot be accomplished reliably and economically by subcontractors.

With these decisions and criteria in mind, the baseline implementation plan for the CELT observatory in each cost element area is described in the sections that follow.

Project Management
The CDP Project Manager, who will be chosen by and will report to the CDC Board, will managethe CDP. The project staff will be co-located with the Project Manager at a single location still to be determined. Owner facilities will be used if satisfactory accommodations can be provided and the location is consistent with staff recruitment constraints. The required project staff will be moved to the observatory headquarters facility prior to the installation and testing of the telescope.

The project manager will recruit and lead key staff. Compensation rates will be established which will allow the Project Manager to attract and retain a highly qualified staff. The Project Manager will recruit from both within and outside the owner institutions.

System Architecture and Analysis

CDP staff will perform most CDP system architecture and analysis tasks. Assistance from outside vendors will be utilized at the discretion of the System Architecture and Analysis Manager.

Project Engineering

CDP staff will perform most project engineering tasks. Assistance from outside vendors will be utilized at the discretion of the project engineer.

Site Acquisition

The effort to collect and process data that will provide the basis for identification and selection of preferred sites will be led by the CDP staff. Much of the site survey effort and data processing will be performed by consultants and contractors hired for that purpose.

As the evaluation process narrows the candidate list, we will begin to discuss with the governments controlling the candidate sites, the potential for acquiring rights to develop the site. The owners will lead this effort. When we have determined the preferred site, the owners will negotiate the purchase of the site for development of CELT.

Enclosure

The enclosure will be designed, fabricated, and erected on the site by a contractor. Before making a final contractor selection, we will evaluate two parallel conceptual design studies, and possibly parallel preliminary design studies, conducted by promising contractors.

Telescope Mount

The telescope mount will be comprised of three subsystems:

1. structure
2. drives and associated controls
3. miscellaneous equipment (cables, plumbing, bearings, etc.)

The baseline implementation approach for the telescope mount is to treat these three areas separately, since it is not likely that any single vendor would have the required diversity of capabilities to fabricate the entire mount.

A structural consultant experienced in large high-performance steel structures will design the structure. The CDP will select a fabricator, with the advice of the structure designer. A contractor selected by the fabricator and approved by the CDP will carry out erection of the structure. Test assembly of critical elements of the structure will occur prior to shipment to the site.

The CDP staff will design the control laws for the telescope drive system, with the help of control system design consultants. A contractor will be selected to complete detailed design and fabrication.

Most additional miscellaneous equipment (cables, plumbing, etc.) will be designed by CDP staff, fabricated by various vendors, and installed by CDP staff.

Optics

Optics will include primary, secondary, and tertiary mirrors. CDP staff will design all optics, and install them following fabrication and testing by vendor(s). A substantial risk mitigation effort will take place in Phase 2 to demonstrate the technical and cost feasibility of the primary mirror manufacturing and test concept. Two sources for prototype segments will be selected (possibly including one within the owner institution family). At least two segments will be fabricated and tested during Phase 2. It may be desirable to establish more than one primary manufacturing source in order to benefit from supplier redundancy, competition, and potential production rate increases. A final selection of primary mirror fabrication contractors will be made during Phase 2.

Optics Passive Support

Passive support systems for optics will be designed and fabricated by outside vendors and delivered to the optics fabrication contractor(s) prior to final testing. During Phase 2 we will review our existing segment support design concept and build and test a prototype using CDP and owner university staff labor.

Optics Active Support

Active support systems for optics will be designed and fabricated by outside vendors. The CDP will seek a single vendor for the integrated primary mirror active system. Separate vendors for the secondary and tertiary mirror supports are admissible options that will be evaluated during Phase 2. A risk mitigation program in Phase 2 will address cost and performance feasibility of actuators and sensors, and multiple prototype actuator and sensor systems will be fabricated and tested during Phase 2.

Adaptive Optics

Under the leadership of the Adaptive Optics Manager, the CDP staff will carry out management and design of the adaptive optics systems in a close working relationship with the SAC. Adaptive optics is currently the highest technology risk of CELT, and promises great scientific return if executed successfully. At the end of Phase 1 there is significant uncertainty in the practical performance requirements. Technology development will be necessary and will be carried out by various outside vendors under the close direction of CDP staff. By the end of Phase 2 key technologies will be developed and understood. System design and predicted performance will also be complete. With these in hand, suitable tradeoff studies will be carried out and requirements for the CELT AO systems will be firmly established. The CDP staff will carry out system integration and test. An expanded description of the adaptive optics development is given in Appendix 1. The AO options, issues and opportunities are described in Volume One, Chapter 9. Dekany (2002) gives a broader description of the adaptive optics implementation plan.

Facilities

The headquarters and summit facilities will be designed by an architect and built by construction contractors under the direction of a CDP facilities manager and architect(s) selected by the CDP.

Software

Software will be designed, coded, integrated, and tested by CDP staff under the leadership of the in-house Software Manager. Very significant software activities will be carried out by other parts of the CDP (e.g., adaptive optics, science instruments, primary mirror control), but will occur under the overall cognizance and guidance of the Software Manager.

Observatory Commissioning

The CDP staff will lead commissioning of the summit and headquarters facilities. Commissioning will include erection of the telescope, assembly and testing of a primary mirror cluster test bed, primary mirror clusters, and secondary and tertiary mirror assemblies.

Science Instruments
Under the leadership of the Science Instruments Manager, the CDP staff will manage the development of science instruments under a close working relationship with the SAC. Science instruments will be designed and built by university/industry teams jointly selected by the Science Instruments Manager and the Principle Investigator, and approved by the Project Manager. Instrument selection, design, and costs will be established at the end of Phase 2. An expanded description of the instrument development plan is given in Appendix 2.

4.3 Administrative Approach

Key aspects of the administration and control of the project are described in this section. A Project Manager who is assisted by a Business Operations Manager and a Project Scientist will lead the CELT development team. The CELT Development Project is an autonomous element of the CELT Development Corporation. The PM is responsible to the CDC Board for achievement of the plan to develop the observatory.

4.3.1 Organization

The CDP will be implemented by the organization shown in Figure 4-1. The following criteria have been used to establish this organization:

1. Products will be bundled into areas for which leadership expertise can most likely be found in a single person.
2. Management and technical interfaces will be simplified.
3. Clear lines of authority will be established.
4. Management overhead will be minimized.

This organization will implement the product-oriented WBS shown in Section 4.5. Lower-level WBS elements are shown as needed under the position title in order to fully characterize product responsibility. A manager who has full responsibility and authority to implement the indicated part of the WBS will lead each element of the organization chart. The roles and responsibilities of each element in the organization follow.

Project Manager
Described in Section 3.3 above

Project Scientist
Described in Section 3.3 above.

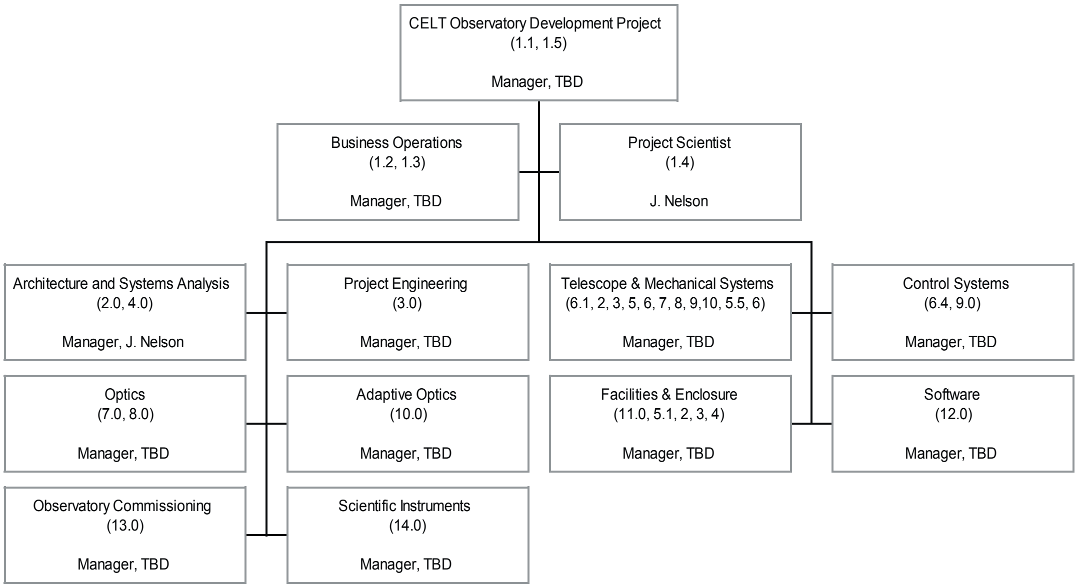

Figure 4-1. CELT Observatory Development Plan.

Business Operations Manager

The Business Operations Manager will be responsible for establishing and operating the business and human resource infrastructure of the project. Key tasks:

1. Establish and maintain CDP business policies.
2. Maintain CDP financial records.
3. Collect and report financial status.
4. Collect and manage CDP operating funds.
5. Supervise purchasing and subcontract activity.
6. Establish human resource policies.
7. Disburse funds as required.
8. Provide a monthly status report to the Project Manager.

Project Engineer

The Project Engineer will be responsible for coordination of CDP technical activities. Key tasks:

1. Coordinate the development and maintenance of technical standards, performance, and interface requirements.
2. Establish and maintain a CDP configuration management system.
3. Establish and maintain CDP technical document archives.
4. Establish and maintain a CDP problem reporting system.
5. Coordinate preparation of observatory test plans.
6. Provide a monthly status report to the Project Manager.
7. Arrange for and conduct project level design reviews

System Architecture and Analysis Manager (SAAM)

The SAAM will be responsible for synthesizing and analyzing the system performance aspects of CELT. Key tasks:

1. Establish the overall observatory conceptual design.

2. Perform trade studies to optimize systems.
3. Prepare analysis models of end-to-end systems.
4. Develop the process for primary mirror alignment and oversee results.

The SAAM will also supervise the selection and acquisition of the CELT site. Key tasks included in this responsibility:

5. Select a site evaluation task leader.
6. Establish site selection criteria.
7. Lead site selection process.
8. Oversee final site evaluation and selection.
9. Lead the site acquisition activity.
10. Provide a monthly status report to the Project Manager.

Telescope and Mechanical Systems Manager

The Mechanical Systems Manager will be responsible for the design, construction, and delivery of the mechanical systems of the observatory as indicated in the organization chart in Section 4.3.1 and the WBS in Section 4.7. Key tasks:

1. Recruit and manage supporting staff.
2. Complete the conceptual design.
3. Define requirements.
4. Negotiate interfaces with other observatory systems.
5. Establish details of implementation approach.
6. Select candidate vendors.
7. Lead the contract definition activity.
8. Monitor and guide selected contractors.
9. Certify compliance of deliverables with requirements.
10. Support observatory integration and testing.
11. Provide a monthly status report to the Project Manager.

Control Systems Manager

The Control Systems Manager will be responsible for the design, construction, and delivery of the electrical systems of the observatory as indicated in the organization chart in Section 4.3.1 and the WBS in Section 4.7. Key tasks:

1. Recruit and manage supporting staff.
2. Complete the conceptual design.
3. Define requirements.
4. Negotiate interfaces with other observatory systems.
5. Establish details of implementation approach.
6. Select candidate vendors.
7. Lead the contract definition activity.
8. Monitor and guide selected contractors.
9. Certify compliance of deliverables with requirements.
10. Support observatory integration and testing.
11. Provide a monthly status report to the Project Manager.

Optics Manager

The Optics Manager will be responsible for the design, construction, and delivery of the optical systems of the observatory as indicated in the organization chart in Section 4.3.1 and the WBS in Section 4.7. Key tasks:

1. Recruit and manage supporting staff.
2. Complete the conceptual design.
3. Define requirements.
4. Supervise the technology development program during Phase 2.
5. Negotiate interfaces with other observatory systems.
6. Establish details of implementation approach.
7. Select candidate vendors.
8. Lead the contract definition activity.
9. Monitor and guide selected contractors.
10. Certify compliance of deliverables with requirements.
11. Support primary integration and testing.
12. Provide a monthly status report to the Project Manager.

Adaptive Optics Manager

The Adaptive Optics Manager will be responsible for the design, construction, and delivery of the adaptive optics systems of the observatory as indicated in the organization chart in Section 4.3.1 and the WBS in Section 4.5.7. Key tasks:

1. Recruit and manage supporting staff.
2. Complete the conceptual design of both AO systems.
3. Select the initial AO systems with the PM, SAC, and PS.
4. Define requirements for each AO system.
5. Negotiate interfaces with other observatory systems.
6. Establish details of implementation approach.
7. Select candidate vendors.
8. Lead the contract definition activity.
9. Monitor and guide selected contractors.
10. Certify compliance of deliverables with requirements.
11. Support integration and testing.
12. Provide a monthly status report to the Project Manager.

Science Instruments Manager

The Science Instruments Manager will be responsible for the design, construction, and delivery of the initial suite of instruments as indicated in the organization chart in Section 4.3.1 and the WBS in Section 4.7. Key tasks:

1. Recruit and manage supporting staff.
2. Complete the conceptual design of candidate instruments.
3. Select the initial suite of instruments with the PM, SAC, and PS.
4. Define requirements.
5. Negotiate interfaces with other observatory systems.
6. Establish details of implementation approach.
7. Select candidate vendors.
8. Lead the contract definition activity.
9. Monitor and guide selected contractors.

10. Certify compliance of deliverables with requirements.
11. Support integration and testing.
12. Provide a monthly status report to the Project Manager.

Software Manager

The Software Manager will be responsible for the design, construction, and delivery of the software systems of the observatory as indicated in the organization chart in Section 4.3.1 and the WBS in Section 4.7. Key tasks:

1. Recruit and manage supporting staff.
2. Complete the conceptual design.
3. Define requirements.
4. Negotiate interfaces with other observatory systems.
5. Establish details of implementation approach.
6. Select candidate vendors as needed.
7. Lead the contract definition activity.
8. Monitor and guide selected contractors.
9. Supervise the development of observatory software.
10. Support observatory integration and testing.
11. Provide a monthly status report to the Project Manager.

Facilities and Enclosure Manager

The Facilities Manager will be responsible for the design and construction of the summit and headquarters facilities of the observatory as indicated in the organization chart in Section 4.3.1 and the WBS in Section 4.7. Key tasks:

1. Recruit and manage supporting staff.
2. Complete the conceptual design.
3. Define requirements.
4. Negotiate interfaces with other observatory systems.
5. Establish details of implementation approach.
6. Select architects and contractors.
7. Lead the contract definition activity.
8. Monitor and guide selected contractors.
9. Supervise construction of summit and headquarters facilities.
10. Provide a monthly status report to the Project Manager.

Observatory Commissioning Manager

The Observatory Commissioning Manager will be responsible for preparing for and leading the assembly and testing of the observatory; and preparing it for operations as indicated in the organization chart in Section 4.3.5 and the WBS in Section 4.7. Key tasks:

1. Prepare and maintain Observatory Commissioning plan.
2. Coordinate summit installation activity starting with the telescope installation.
3. Coordinate assembly of primary, secondary, and tertiary mirrors and transport to summit.
4. Provide transportation services for observatory staff.
5. Support the incoming director in preparing for operations.
6. Coordinate summit test activities.
7. Provide a monthly status report to the Project Manager.

4.3.2 Financing

The CDP will manage its own finances under the day-to-day direction of the business operations manager. The chief financial officer of the CDC will make funds available to the CDP account(s) on a quarterly basis. These funds will be in the amounts of the approved obligations budget plan plus reserve. The funds will be available at least one full quarter before the quarter in which they are to be expended.

4.3.3 Fiscal Integrity

Safeguards will be established to assure the CDC that CDP funds are properly utilized. These safeguards will include regular independent audits of CDP finances and CDC approval of contract commitments and disbursements in excess of limits to be determined.

4.3.4 Project Control

Controls will be established and used to assure that cost and schedule performance relative to the project plan are evaluated at regular intervals. Information will be collected so that deficiencies can be identified and corrected in a timely way.

Design Control
The design of the CELT observatory will be developed in a systematic way in response to a controlled set of hierarchical design requirements and standards. The Project Engineer will lead the development and change control of these requirements and standards. The initial issues and changes will be prepared by responsible engineers and approved by the responsible managers, and the Project Manager as appropriate.

The design of the observatory as a whole will be subjected to formal review (with external participation) at the conceptual, preliminary, and final design stages. Observatory subsystems will be subjected to formal review (with external participation) at the preliminary and final design stages. Critical manufacturing processes (e.g. primary segment manufacture) will be subjected to formal production readiness reviews.

Cost Control
A budget plan will be established and updated biannually. Costs will be planned and actuals tracked monthly, down to Level 2 in the work breakdown structure (WBS), described in more detail in Section 4.5. All major subcontractor costs (except for fixed price contracts) will be included in this metric. The project manager as required will authorize allocation of reserve. A metric of the amounts and reasons for reserve expenditure will be maintained for presentation at biannual cost reviews. Both AO and Scientific Instruments are handled as fixed cost items, and suitable reserve will be internal to their budgets.

Schedule Control
A top-level schedule will be established by the project manager and updated biannually by the responsible CDP manager. Detailed schedules will be established and updated biannually for each Level 2 WBS area. Milestone achievements from these detailed Level 2 schedules will be tracked monthly, down to at least Level 3. Tracked milestones will be selected by the manager responsible for each Level 2 WBS area and approved by the project manager. These milestones will be product-completion-oriented and will be as uniform in cost value as practical across various CDP areas.

4.3.5 External Review

A review committee will be formed to review the project's technical and programmatic progress on a biannual basis. The committee will be populated with approximately six experts from outside the CDP. Committee members will be chosen for their relevant and recent experience in areas important to CDP success. The CDP Project Manager and the CEO of the CDC will jointly select committee members.

4.3.6 Reporting

In addition to frequent informal communications between the Project Manager and the CEO and other special reports which may be required by the owners from time to time, the CDP will prepare the following regular reports and presentations:

1. A short weekly project highlights email will be distributed to the owners and appropriate interested parties.
2. A bimonthly written report will be prepared which includes achievements during the last period, plans for the next period, issues (with resolution plans), financial status, and schedule status. This report will be available one week after the start of every other calendar month.
3. A Project Manager status assessment will be presented to the SAC at their regular meetings.
4. A biannual presentation will be made to the CDP external review committee by key project staff. This presentation will contain current technical and financial information for all key project areas.
5. The Project Manager and Business Operation Manager will present project status to regular CDC board meetings.

4.4 Schedule

The implementation of the CDP will take ten years from the time that the project is initiated until science operations begin. The integrated schedule for the CDP is shown in Figure 4-2.

4.4.1 Critical Path

As shown in Figures 4.2, the critical path flows through site acquisition, summit facility construction, telescope installation and testing, and instrument installation and testing. These activities are unavoidably serial. No explicit reserve is identified.

Site Acquisition

Timely site acquisition is the single most important schedule driver of the CDP. It drives the schedule in two ways. First and most importantly, summit infrastructure construction cannot begin until full access and title to the selected site is achieved. This process can be long and its outcome uncertain. The CDP implementation schedule includes a credible but aggressive site selection and acquisition process. It requires a site selection 36 months from the start of the project, and a final site access agreement ("acquisition") six months later. Second, uncertainties in the observatory site drive design details. The design activity will accommodate a range of site characteristics until the selection is made. There is no slack in the site selection and acquisition schedule.

Summit Facility Construction

Summit facility construction will span three summers starting with 1) construction of foundations for the enclosure, building, and telescope, followed by 2) building construction, and 3) enclosure installation. No explicit slack is provided in the schedule, however work is not scheduled during the winter environment that employs the following proven management tools and processes.

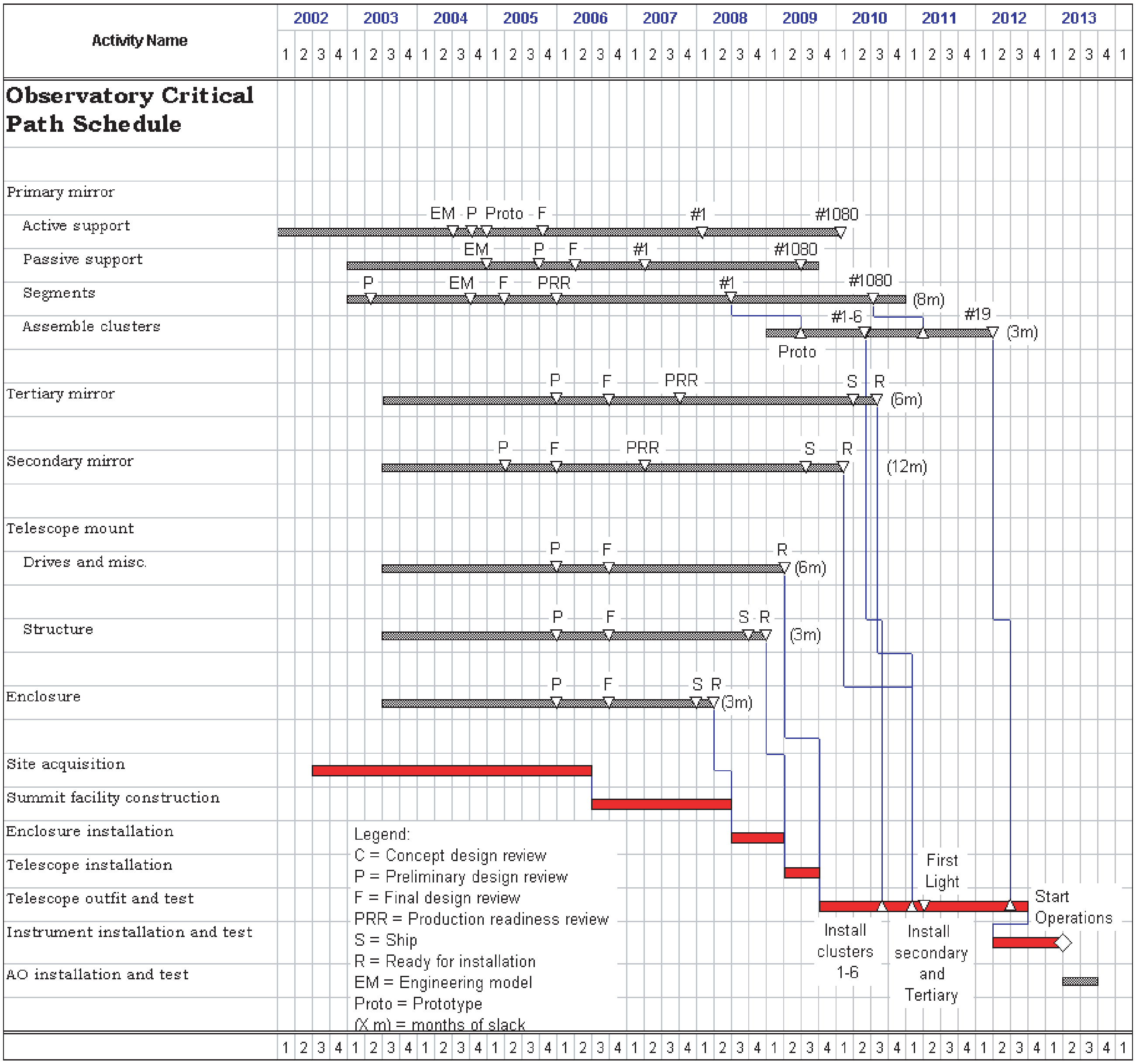

Figure 4-2. CDP Critical path milestones.

Telescope Installation and Testing

These activities are scheduled to begin immediately after enclosure installation is finished and the summit building can support the workforce and equipment needed to complete them. The telescope structure will be transported to the summit in the largest sub-assemblies practical and assembled in place. A full year is provided to outfit the telescope and test bearings and drives after the structure is installed. This will make it possible to eliminate overlap between the dirty and disruptive heavy mechanical assembly activity and the primary mirror installation.

The primary mirror will be installed in two stages. First light will follow installation of six primary mirror clusters (114 segments). No slack is provided in the telescope assembly and testing activities.

Science Instruments and Adaptive Optics Systems Installation
The science instruments and the adaptive optics systems will be installed during the last six months of the development schedule.

4.4.2 Off-critical Path

The elements of the observatory that feed into this critical path have slack in the schedule as shown in Figure 4-2. It is essential that the slack provided for these elements is consistent with the schedule risk of these off-critical path items.

Primary Mirror
The primary mirror manufacture, including testing, is of special interest in that it is the single most costly element of the observatory, as well as the highest risk (barring AO). In order to mitigate this risk, initiation of fabrication activities for the primary mirror optics will precede all other observatory fabrication activities. This early fabrication start will provide a five year period to complete fabrication and testing of the primary mirror, with comfortable slack of around eighteen months for initial and final segment need dates. A primary mirror cluster test bed assembly activity has been included in the schedule one year before the start of final primary mirror cluster assembly in order to further mitigate schedule risk in this area.

Secondary and Tertiary Mirrors
The large secondary and tertiary mirrors are also relatively high-risk schedule items and are required to produce first light images. Nine months of slack have been provided in the fabrication schedule for these mirrors. An additional four months of integration and functional testing in their mirror cells has been provided prior to installation on the telescope.

4.4.3 Key Phase 2 Milestones

Key Phase 2 milestones are shown in Figure 4-3.

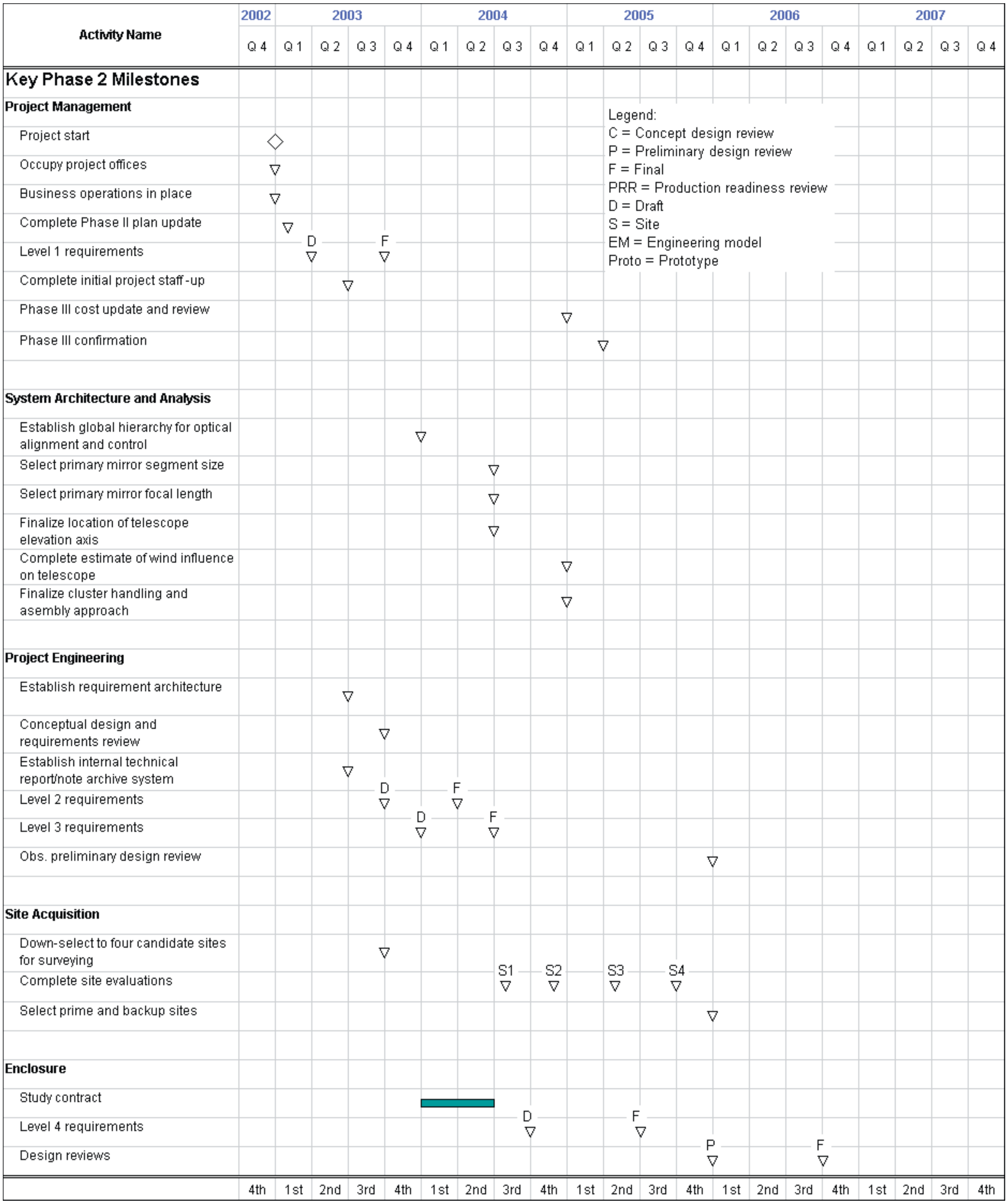

Figure 4-3a. Key Milestones for Phase 2, page 1.

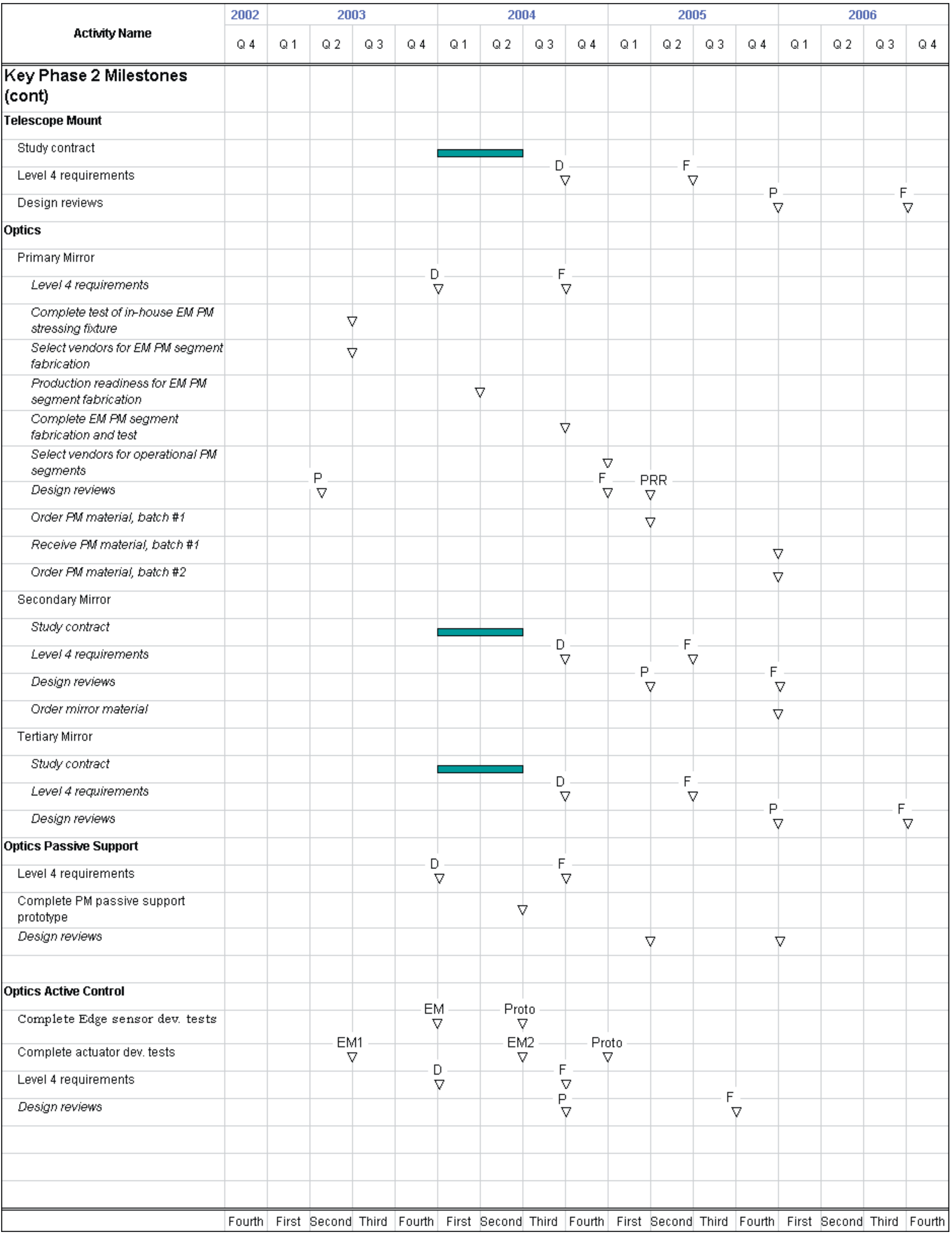

Figure 4-3b. Key Milestones for Phase 2, page 2.

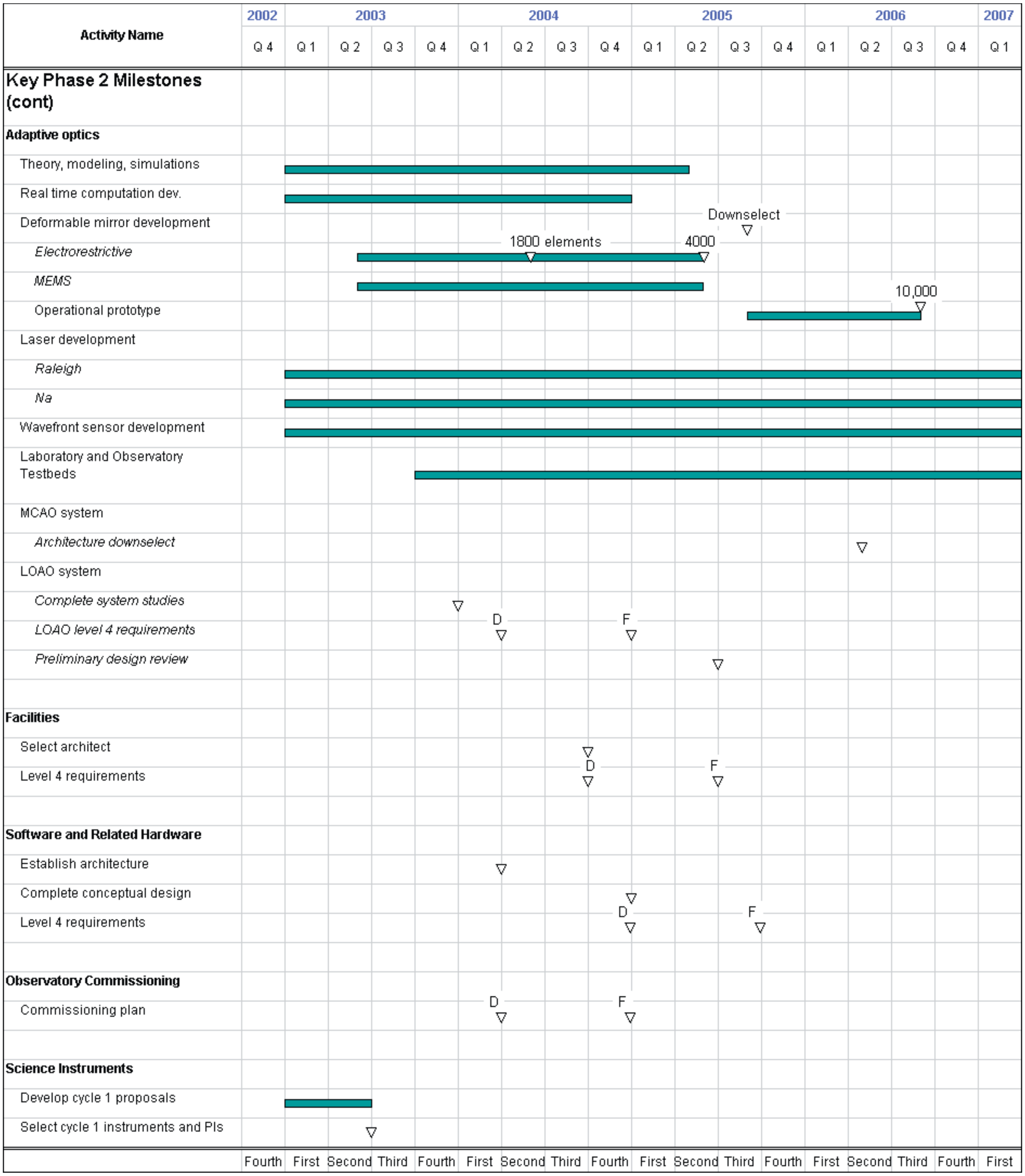

Figure 4-3c. Key Milestones for Phase 2, page 3.

4.5 Risk Assessment

The core of the risk mitigation strategy for CELT is to select and maintain the most highly qualified project team (including contractors and suppliers), and to utilize that team within a project management environment that employs the following proven management tools and processes.

- Development of a detailed work breakdown structure.
- Development of a detailed budget to match the work breakdown structure.
- Development of specific milestones for each aspect of development.
- Use of outside reviewers in a well-defined structure of conceptual design, preliminary design, and critical design reviews.
- Disciplined written response to the concerns raised at these reviews.
- Detailed documentation of all designs and decisions made rapidly available to all participants.
- Creation and use of an extensive error budget to make quantitative choices between performance, budget, and schedule.
- Effective balancing of scientific objectives and requirements.

Many aspects of CELT will be challenging. We believe that employing these tools and processes will address the usual challenges of a project of this scale and complexity.

Beyond the usual challenges posed by a project like CELT, the CELT design concept poses certain specific programmatic and technical risks that must be explicitly mitigated in order to provide assurance of a successful outcome. Mitigation will take various forms, including the development of engineering models in Phase 2, scope/requirement choices which depend on Phase 2 study outcomes, appropriate allocation of cost and schedule reserves, and the judicious selection of vendors (as well as possible alternate sources). The sections below describe the risks that have been identified in the area of cost and technology.

Technology risks carry the uncertainty that technology solutions may not exist to achieve the performance goals. Cost risks carry a large uncertainty in the cost estimate, large enough to have a significant impact on the overall project cost.

The activities that we will use in Phase 2 to mitigate the risks identified below are described in Section 4.6.1.

Technology Risks

Adaptive optics

The adaptive optics systems carry the highest technology risk for CELT. The technology for AO systems for 8 to 10-meter telescopes is today state-of-the-art and is still under active development. The technology for a 30-meter telescope does not exist.

The analytic and simulation tools required for the design are currently too immature for reliable application to a 30-meter telescope. Techniques for addressing the finite distance to and the finite thickness of the sodium layer have not been developed or tested. The large aperture of CELT will require multiple laser guide stars, and the use of such a system is only now being studied and has never been demonstrated. AO for CELT will require deformable mirrors with thousands of actuators; high power, appropriate format guide star lasers; and large format, low-noise, fast-frame, visible and near-infrared detectors. None of these exist today.

For mid-IR optimized work, cryogenic deformable mirrors are required but have not been demonstrated.

New controls, architectures, and algorithms are required to meet the real-time computing challenges. The software for CELT AO is significantly more complex than that of existing AO systems.

All of the above factors contribute to the high technology risk.

Impact of the wind on the telescope

The very large astronomical opening of the dome may allow wind forces to induce unacceptably large telescope motion. Currently we do not have an adequate estimate of these wind forces to assure that a particular structure design has adequate stiffness, or that the dome design has adequate shielding; or that the active control of the secondary will be adequate.

Impact of the wind on the primary mirror control

The very large astronomical opening of the dome can potentially allow wind forces to induce unacceptably large segment motions. Currently we do not have a good estimate of these wind forces to assure that our proposed segment passive and active control systems will provide adequate stabilization when perturbed by wind forces.

Robustness of the actuator design

The actuator system has no redundancy. Failure of an actuator will result in its segment sending light to an unpredictable region of the focal surface; thus failed actuators should be replaced before observing can proceed. On the Keck telescopes the actuator failure rate is sufficiently low that this is not a problem. However, there are 108 actuators on each Keck telescope, and there will be 3240 actuators on CELT. Thus the failure rate must be substantially lower for the CELT actuator design.

Cost Risks

The telescope enclosure design

The enclosure will be a major part of the total observatory cost. Features such as wind shielding, crane access, thermal control, and ventilation of the telescope are expected to strongly impact the cost of the enclosure. In addition, site characteristics such as wind, ice loads, precipitation, temperature, soil conditions, and seismic conditions may strongly affect the enclosure design and cost.

The segment fabrication process

Although we have a concept for the segment fabrication process, we have not presented this in detail to candidate segment fabricators. Thus there is significant cost risk in this process.

The actuator design

The Keck actuator design is too costly (~ $10K per) to fabricate the large number required for CELT. In Phase 1 we set a goal of about $2K per actuator for CELT. Actuator design and prototype work achieved in the CELT concept phase has begun to approach this goal.

The displacement sensor design

The Keck displacement sensor design is too costly (~ $10K per) to fabricate the large number required for CELT. In Phase 1 we set a goal of about $0.5K per sensor for CELT. Conceptual designs of the CELT sensors suggest this goal is feasible.

The secondary and tertiary fabrication process
Significant uncertainty exists in the polishing and testing processes to be used to fabricate the convex secondary mirror and the flat tertiary mirror. Thus the cost estimates currently carry large cost risks.

Science Instruments
Because of the large focal surface and the demands of the adaptive optics image quality, the science instruments will require techniques beyond those used by existing instruments. Image slicer and integral-field technologies will need to be refined; cryogenic actuation made more reliable; grating mosaics will be common-place; large optics fabrication and support will be required; and fiber optics techniques will need to be brought to a higher level of maturity, reliability and performance. Although these are feasible extensions of existing technologies, the cost uncertainty is currently large enough that the cost might have a significant impact on the overall budget.

In addition, schedule uncertainty might also carry a significant cost impact. Some of the larger Keck (and VLT) instruments have taken 6-10 years for design, fabrication, and commissioning phases. CELT instruments will be larger and likely more complex than those we have built to date for Keck. Delays in the conceptual design, instrument selection, design, and construction carry associated cost risks.

4.6 Task Content

A detailed budget/work breakdown structure is contained in Section 4.7. The control of these tasks is described below for both Phase 2 and Phase 3.

4.6.1 Phase 2 Activities

Project Management
The first priority during Phase 2 for the Project Manager will be to build a strong project leadership team. The highest priority position to fill is that of Business Operations Manager, who will be charged with establishing the project administrative infrastructure. The Project Manager will focus on technical management and engineering recruitment, while the Business Operations Manager will focus on administrative staff recruitment. Project management will occupy a project office located so as to maximize key personnel recruitment success and efficiency of project operations. The project key milestone chart (Figure 3-3) shows that the Project Manager is to be selected and in place three months prior to the formal start of Phase 2. This lead time is designed to allow the Project Manager sufficient time to arrange for project office facilities and to recruit a Business Operations Manager (and possibly other key staff) so that the project productivity can ramp up quickly at the time of formal Phase 2 project start. Funding for this transitional period needs to be provided as augmentation to Phase 1 funding. It is implicit in this plan.

System Architecture and Analysis
Key results are needed to set the baseline design for CELT and these will be overseen with the goal of setting the proper baseline design and reducing technical and financial risk. Scientific requirements will be firmed up in conjunction with the Science and Advisory Committee.

During the first two years we will establish the key optical parameters that define the telescope, including the primary mirror focal length, the number of primary mirror segments, and the location of the elevation axis relative to the primary mirror. In order to set these parameters we will study the sensitivity of segment misalignment and the manufacturability of segments as a function of their asphericity.

The plan for optical alignment of the system will be developed, including both initial and periodic alignment. A key component of this will involve the use of wavefront sensors and edge sensor information. An alignment camera will be designed that is capable of determining proper segment phasing and tip-tilt as well as distinguishing between primary and secondary misalignments.

In the first two years of Phase 2 we will evaluate telescope wind loads by collecting and making our own analyses of the existing measurements on candidate mountain sites and at existing observatories. We will also use extensive computer modeling of the effect of wind on candidate enclosure designs. These will determine the amount of shielding provided by the enclosure and the adequacy of assumed telescope structure requirements. In the first two years of Phase 2 we will address this risk using the same tasks listed above. In addition, we will model the response of the segment active and passive controls to a variety of wind force distributions.

Project Engineering

During Phase 2, the Project Engineer will prepare observatory Level 2 requirements (e.g., technical standards) and Level 3 requirements (e.g., observatory error budgets). He or she will coordinate and assist other CELT technical managers in preparing Level 4 requirements (e.g., enclosure specifications) as well as interface agreements.

Two important project level technical reviews will be conducted by the project engineer, the observatory conceptual design and Level 1 requirements review and the observatory preliminary design review.

Site Acquisition

Since site acquisition is in the project critical path, before Phase 2 begins we will generate a preliminary list of candidate sites using satellite data processed by an outside vendor. We will also acquire suitable site testing equipment and hire testing staff (if funding is available).

In Phase 2 we will vigorously pursue the determination of the best technical sites and work with the owners to prepare the case for acquiring the desired site from the site owners (governments, etc). We will carry out numerical modeling of the atmosphere, aimed at estimating the seeing, at each site to reduce the list of candidate sites. We will then make an assessment of the technical and political accessibility of the candidate sites. In parallel with some of these activities we will mount a direct measurement campaign at several sites to measure the seeing and related atmospheric properties and to assess the weather conditions. These site-testing activities will take about two years at each site, in order to gain sufficient confidence in the results.

Purchase of the rights to the site will take place at the outset of Phase 3.

Enclosure

The enclosure design is critical to both technical (wind shielding, telescope servicing) and cost issues. We will vigorously draft requirements and select candidate vendors for conceptual studies of enclosure designs. We will iterate with the vendors to establish requirements that are tolerable to us and adequate to achieve the most economical design. We will establish a reference site to allow design studies to proceed. We will downselect to a single preferred enclosure and obtain reliable cost estimates for it.

Telescope Mount

The telescope mount performance is pivotal to several technical and system issues. The impact of wind loads, segment handling, and optical system optimization are all critically dependent on telescope structure performance. We will initiate studies with outside contractors in order to improve upon our existing conceptual design. We will iterate with the requirements and the mount design to optimize the mount, and select a baseline design that meets our needs.

Optics

Segment fabrication cost is critical to CELT. We will vigorously develop and prototype our proposed method (planetary stressed mirror polishing, PSMP) in partnership with outside vendors. We will also explore other potential fabrication methods.

We are currently proposing the following steps to fabricate the segments. These were successfully used to create the segments of the Keck telescopes.

1. blank acceptance and analysis
2. convex side grind and shine
3. concave grind
4. planetary stressed mirror grinding and polishing
5. contact test
6. optical test - round
7. cut
8. optical test - hex
9. ion figure
10. warping harness

Since a significantly larger number of segments are required for CELT, we believe that Phase 2 development for steps 4, 5, 6, 8, 9, and 10 is required to reduce the cost risk for segment fabrication. We simply list here the tasks that will be used to reduce the cost risk of these steps.

4. planetary stressed mirror polishing
    - design a prototype stressing fixture
    - build stressing fixture
    - mechanically and optically test stressing fixture
    - use and test on planetary polisher
    - cost estimate
5. contact test
    - detailed design and error analysis
    - build prototype and reference
    - test prototype
    - cost estimate
6. optical test - round
    - detailed design and error analysis
    - cost estimate
8. optical test - hex
    - detailed design and error analysis
    - cost estimate

9. ion figure
    - detailed design and error analysis
    - build prototype
    - test prototype
    - cost estimate
10. warping harness
    - understand Keck failure to achieve expected iterative improvement
    - detailed design and error analysis
    - cost estimate

Candidate vendors for these areas will be involved as teammates with CDP staff early in Phase 2 so that transfer of the developing processes and technology will be effective and economical. In addition to the above tasks we will vigorously pursue an overall task to study alternatives to any and all aspects of the above concept. Considerable progress has been made in the optics fabrication industry since the Keck segments were made, and we will study these for their applicability to reducing the cost of the CELT segments.

We will develop through contracts with vendors an acceptable technique for fabricating the secondary and tertiary mirrors, with emphasis on testing methods. We will select vendor(s) for primary segment production and secondary and tertiary fabrication, and initiate assembly of production facilities.

Secondary and tertiary mirror production will be challenging. In Phase 2 we will actively pursue the methods already under development at LLNL to test large convex secondary mirrors. In Phase 2 we will also consult extensively with potential fabricators about the polish and test processes that might be used, and we will develop a detailed understanding of the cost tradeoffs that may be made in the fabrication. After the first two years of Phase 2 we will have reduced the cost risk for both of these components.

Optics Passive Support

We have a conceptual design for the segment support; we will review this design, then build and test a prototype. The interface of this support to the segments themselves and to the underlying support structure, and the segment handling and replacement requirements, make this piece remarkably complex. We will work on these interface issues in detail in Phase 2.

The passive supports of the secondary and tertiary are challenges in and of themselves. We will work with industry and consultants to produce an appropriate design for the supports.

Optics Active Control

The active control system for the primary mirror requires edge sensors, actuators, and a control algorithm. With 1080 segments and 160 spares, we need a total of 6204 + 1034 = 7238 edge sensors, and 3240 + 540 = 3780 actuators.

We will design, fabricate, and test our design for capacitive edge sensors. We will build and test two cycles of engineering models to confirm that they meet the performance requirements; and determine the cost of producing sensors in large numbers. We will also work to understand the noise sources experienced in the Keck edge sensors. CELT edge sensors will be bonded or coated onto the segments, so these techniques will be developed. In addition, we will work to simplify the wiring to the sensors, to ease assembly procedures. Keck style sensors require a cable going to each half of the sensor. We hope to avoid one of these cables.

The actuators needed for CELT (3780) must be very reliable and move smoothly. In Phase 2 we will define requirements for stroke and lifetime. We will review and test the voice-coil prototype actuator made in the conceptual design phase, modify the design as necessary, and make additional copies for exhaustive test. We also hope to make another type of actuator and thoroughly test it. We will determine the cost of producing actuators in large numbers.

The control algorithm for controlling segments will be further developed. Algorithms and protocols for combining information from edge sensors and wavefront sensors, as well as predetermined lookup tables will be developed, and global performance estimated.

The electronics and related distributions system for operating 3240 actuators and 6204 edge sensors will be developed.

The active controls for adjusting the positions of the secondary and tertiary mirrors will be designed and evaluated.

Adaptive Optics

AO system designs for both AO systems will be developed and simulated. Key components for the AO systems (lasers, deformable mirrors, wavefront sensors, control algorithms) will be pursued both in-house and with outside vendors and consultants. By the end of Phase 2 we will have sufficient knowledge about the systems and components to define the AO requirements and cost of the proposed systems.

In Section 4.5 above we listed the high technology risks associated with adaptive optics. Here we describe the tasks that will be carried out in Phase 2 to mitigate those risks. They fall into three major categories: theory and simulation development, component technology development, and laboratory and field demonstrations.

We will extend the analytic understanding of AO systems to include the larger and more complex systems required for a 30-meter telescope. We will develop a high-speed, parallelized simulation code and use that code to make performance-cost trades in the design of the two AO systems. This code will be used to address many design issues, some of which are listed in Appendix 1. The code will be scalable to operate on both desktop workstations and on high-performance clusters (e.g., Sun networks or the Beowulf system at Caltech's Center for Advanced Computing Research) and dedicated multi-processor platforms (e.g., the supercomputers at LLNL or the San Diego Supercomputing Center).

We will fund a small number of candidate approaches for addressing the technology risk of individual AO subsystem components. At the beginning of Phase 2 we will make a systematic study of these candidates and select those most likely to provide solutions at acceptable cost. The table below gives an initial list of candidate technologies to be pursued.

Table 4-1. Candidate Technologies

Component	Some alternative technologies
Deformable mirror	Electrostrictive arrays (Xinetics, Inc.), MEMS (Boston Micromachines, others)
Visible wavefront sensor detector array	CCD arrays (Marconi. LL), Hi-Visi arrays (Rockwell Scientific)
IR wavefront sensor detector array	HgCdTe arrays (Rockwell Scientific), InSb arrays (Boeing)
Na guide star laser	Sum frequency slab Nd:Yag (U Chicago/Lite Cycles), Dye lasers (LLNL), Erbium doped fiber lasers (LLNL)
Rayleigh guide star laser (if needed)	361nm tripled Nd:Yag and Nd:YLF (Coherent, others)
Real-time computer	DSPs (TI), General purpose processors (Intel, others)

Funding the development of all these component technologies will be expensive. Fortunately, CELT AO development will occur in an environment of continuing AO development on existing telescopes; parallel development of European and other extremely large telescope projects; the NSF-funded Center for Adaptive Optics (CfAO), headquartered at UC Santa Cruz; and the development of large deformable mirrors for space-based applications. A close, collaborative relationship with the following potential partners will increase the leverage of CELT investments and will be actively pursued.

CARA	Laser guide star AO development at Keck Observatory
CfAO	Theoretical and simulation development, laser development, MEMS
ESO	Multi-conjugate AO Demonstrator (MAD) for the Very Large Telescope (VLT) Observatory
Gemini	MCAO system development, laser development
LLNL	LGS AO, laser development
MPIA (Heidelberg)	3-D model turbulence generator
JPL	High actuator count deformable mirror development
Padova	Pyramid wavefront sensor development
U of Arizona	Wavefront sensor development, AO for the Large Binocular Telescope (LBT)
UC Berkeley	MEMS development, high count deformable mirrors
U of Chicago	Laser development, reconstructor algorithms
U of Illinois	Rayleigh beacon AO at Mt. Wilson Observatory (MWO)
USAF	Starfire Optical Range, laser development

The most promising area for collaborative development is likely to be in the area of guide star lasers, as nearly all existing telescopes will benefit from improved laser maturity. The CELT 2003-2006 AO development budget for laser development (estimated. $3M) assumes significant cost sharing with collaborating institutions.

CELT will actively pursue partnering relationships to ensure specific progress in areas that are crucial to the science return of the observatory. Thus, we plan to invest in deformable mirrors, lasers, and wavefront sensors at a level sufficient to meet our performance goals, while seeking partnerships to reduce total cost and/or accelerate the schedule. This is particularly true for guide star laser development, where a failure of the community to collaboratively advance laser technology would likely result in significant cost risk to CELT.

We will use laboratory and/or field demonstrations to

- validate the theoretical and numerical simulation analysis upon which the AO system architecture will be based,
- validate key component performance,
- guide software functional requirements for CELT, and
- train a generation of AO engineers who will carry forward their expertise to CELT system design, integration and test, and operations.

Laboratory demonstrations have the advantages of using a controlled environment that is known and can be repeated. Field demonstrations have the advantage of testing the architecture, components and software in real-world conditions. For field-testing we will use the existing Palomar Multi-conjugate Adaptive Optics (PALMAO) Testbed and the Keck Adaptive Optics System.

Science Instruments

The cost and schedule uncertainties can be mitigated in part by the instrument selection process, management of the design and construction, and the use the expertise of industry to build large, and complex technology projects. Extensive Phase 2 prototyping and development activities are envisaged to bring key technologies to a level of maturity consistent with the demanding performance goals of the instrumentation.

We will use a combination of our own experience with Keck instruments in conjunction with outside industry, where practical, to match instrument concepts with evolving science goals. This method will maximize science output within the constraints of cost and schedule. We will further mitigate risks by full-system modeling of all components in the instrument to support design and selection decisions.

For all science instrument activities we will use the same management methods used for the remainder of the observatory. This was not done for the Keck instruments, and as a result there were significant cost and schedule overruns.

In the design and construction phases we will explore use of fixed-price contracts with industry and, where appropriate, contracts with specialized university and government laboratories. We anticipate continued involvement of individual and collaborative university groups, especially in the concept phases, and in the final integration, test and commissioning phase as well. Strict project management disciplines will be applied across the board to control schedule and cost.

Facilities

Requirements for facilities will be thoroughly developed and preliminary designs with an architect will be carried out.

Software and Related Hardware

The Software Manager and Software Architect will vigorously study the approach to developing and maintaining the varied kinds of software needed for CELT. Requirements will be developed. A software architecture will be defined that incorporates the special software needs of the AO system, the science instruments, and the optics active control systems.

Observatory Commissioning
The strategy for observatory commissioning will be developed. The commissioning schedule will be refined. Segment handling, cluster assembly, cluster installation and removal from the telescope, and mirror coatings will be critical aspects of this. Optical and mechanical alignment will be critical parts of this plan.

4.6.2 Task Content of Phase 3

Project Management
Project management will continue to build, maintain, and lead project staff, lead the planning for moving staff to permanent headquarters, and provide the infrastructure for financial and technical management of the project. The Project Manager will allocate financial reserve as required to achieve the approved project plan.

System Architecture and Analysis
Detailed plans for optics assembly and initial alignment will be developed. Plans for periodic calibration and alignment will be developed. Alignment hardware and software will be developed and delivered in a timely way in support of the facility integration and commissioning. System Architecture will be available to carry out calculations in support of any suggested tradeoffs in the design implementation that may be required.

Project Engineering
Project engineering will lead the maintenance of the design requirements and lead the observatory final design review. During construction and commissioning, project engineering will administer the project's Failure and Repair process and coordinate routine and trouble-shooting tests as required.

Site Acquisition
The site will be selected and rights obtained for the construction and operation of CELT at that site.

Enclosure
The detailed design will be completed, a construction contractor selected, the enclosure fabricated and tested at the vendors site, the enclosure shipped and erected at the CELT site, and final performance testing carried out. The enclosure will be accepted in time for installation of the telescope.

Telescope Mount
The detailed design of the telescope structure will be completed, including bearings, drives, encoders, and suitable handling equipment and procedures. The vendor will be selected, the telescope built and tested at the vendor's site. The telescope will be shipped to the CELT site and erected inside the enclosure. Suitable functional tests will be carried out and the telescope will be turned over for the rest of optics installation and commissioning.

Optics
Primary, secondary and tertiary mirrors will have their detailed design completed. Vendors will be selected, and the optics will be fabricated. Shipping of segments in a timely way for the assembly of clusters will be arranged. Optics will be thoroughly tested and support systems installed and tested. Optics will be installed in the telescope in preparation for commissioning.

Optics Passive Support
The detailed design of the passive support systems will be completed. Vendors for fabrication will be selected. Fabrication will be carried out in a timely way to allow testing of segments at the optical vendors' facilities, and later to allow integration of the segment passive supports with the finished segments into clusters.

Optics Active Control
The detailed design will be completed and vendors selected for the various components. Fabrication will take place in a timely way, to ensure components are ready for integration and commissioning into clusters and on the telescope.

Adaptive Optics
The detailed designs of the AO system(s) will be completed. Vendors will be selected for key component fabrication, working closely with appropriate CELT AO staff. Integration of the AO system and subsequent testing will take place in a laboratory environment, prior to shipping and assembly on the telescope. Dekany (2002) gives a full description of the AO development plan. Some of the information in that report is collected below in Appendix 1, "Details of the Adaptive Optics Development Plan."

Science Instruments
The detailed designs of the science instruments will be completed. Vendors will be selected for key component fabrication, working closely with appropriate CDP staff. Integration of each instrument and subsequent testing will take place in a laboratory environment, prior to shipping and assembly on the telescope. A description of the instrument development plan is given in Appendix 2, "Details of the Instrument Development Plan."

Facilities
The detailed designs of the summit and headquarters facilities will be completed. Contractors for the construction will be selected and construction completed

Software and Related Hardware
Software and hardware detailed design to address the functional requirements will be carried out. All software tasks will be included in the design. Tasks will be detailed and prototype software written and tested. During this phase increasingly powerful and robust prototype software will be developed and tested. At the time of commissioning, operational software and hardware will be complete in support of commissioning activities. Further upgrades and improvements will be available for the beginning of operations.

Observatory Commissioning
Detailed plans for the commissioning will be developed, including all aspects of handling and assembly of the components. Detailed plans for installation and alignment will be developed, including mechanical, optical and software components. As hardware comes to the site, the commissioning team will provide oversight to integration tasks, and lead the most critical ones. Commissioning will include the integration and test of the optics, telescope motion, science instruments, and the AO systems.

4.7 Budget

This section provides explanation and further detail on the observatory development portion of the overall CELT budget shown in Figure 3-2. Details down to Level 2 in the work breakdown structure area are shown in Figure 4-3. Costs for Phase 2 (fiscal years 2003-05) are based on quarterly estimates. Costs shown are in real-year dollars. The time phasing is based on cost commitment requirements (sometimes referred to as obligations) and has been developed in concert with the schedule described in Section 4.4.

4.7.1 Basis of Estimates

The key underlying assumptions on which CDP costs are based are:

1. A dedicated, autonomous project team will be formed that will provide its own business infrastructure and cost environment (independent of the cost and burden structures of the owner institutions).
2. Key staff salaries will be established at levels that will attract and retain highly qualified people.
3. Funding will come from private sources, which will mitigate expenses associated with special implementation requirements that often accompany public funds.
4. The CDC will allocate funding to the project in an uninterrupted and predictable way, in accordance with the spending plan approved.

Each element in this budget has been individually estimated based on a variety of techniques ranging from bottom-up estimates to similarity and scaling techniques. Estimates were initially made in calendar year 2000 dollars and inflated outward as warranted by the schedule. An average inflation rate of 2.5% per year has been assumed. Highlights of the basis of the most critical budget elements follow. We follow the structure of the WBS.

Project Management

All costs associated with the staff that will manage and execute the CDP have been estimated from the bottom-up with a cost estimation spreadsheet tool that accounts for labor rates of various staff positions, inflation (2.5%/yr.) merit increases (3%/yr.), and benefits (22.5%). Management and engineering staff are accumulated in each Level 2 WBS area as appropriate to those tasks.

The cost of preparing, executing, and administering subcontracts are included in the project staff budget. No specific burdens are applied to subcontracts. If the CDC requires external legal or other oversight costs, these costs will be borne by the CDC, outside of the CDP budget.

The CDP will provide liability insurance (or self-insurance) to CDP employees. No provision for these costs is made in this budget.

System Architecture and Analysis

Cost estimates are based on bottom-up effort for many issues and on scaled up estimates for the alignment camera, based on Keck experience.

Project Engineering

Costs are based on bottom-up estimates of costs of effort for system engineering, and quality/reliability/maintainability engineering.

Site Selection and Acquisition

Site "acquisition" refers to the process of acquiring legal title to build on and utilize the chosen site for the required duration of development and operations. The cost of site acquisition is difficult to estimate since a wide variety of diverse sites will be evaluated during the selection process. The estimate for this cost is based on the cost of acquiring the Keck site, inflated to the CELT site acquisition year(s). Site survey and selection costs have been added to this acquisition estimate.

Enclosure

The enclosure cost is based on bottom-up in-house development and management needs, and pivotally on a cost estimate for a 90-m enclosure by Temcor (Carson, CA). Their estimate of $18M from an experienced firm is assumed reliable, and the restrictions of using a geodesic dome style structure (restricted point loads) are believed to be tolerable.

Telescope Mount

The mount cost is based in bottom-up in-house engineering efforts, experience with Keck, and an assumed net installed cost of steel structures of $20/kg. Bearing and drive costs are based on a conceptual design effort for CELT by Vertex/RSI (Fort Walton Beach, FL).

Optics

Costs for optics are based on bottom-up in-house engineering and contract management costs, and on external estimates. Mirror material costs are based on vendor estimate of $100/kg; segment polishing costs are based on vendor estimates of flat mirror production costs of $15K/m^2 (doubled by us for segments). Secondary and tertiary costs are based largely on the actual cost of design/fabrication/integration for the SOAR optics.

Optics Passive Support

Most segment costs are based on a conceptual design for CELT by Steve Gunnels. The design includes a detailed cost estimate of $1100/segment, which we inflated to $2K/segment. Support for the secondary and tertiary is based on the Southern Astrophysical Research Telescope, SOAR.

Optics Active Control

The primary mirror active control costs are based on bottom-up in-house engineering efforts and a cost of $2K/actuator, consistent with the prototype built for CELT. The sensor costs ($0.5K/sensor) are based on Keck electronics costs. The capacitor mechanical part is only metal coatings on segment edges, so the large costs of mechanical parts for Keck sensors are not relevant. Costs of secondary and tertiary control systems are based on Keck and on engineering judgement.

Adaptive Optics

Adaptive optics costs are based on the experience gained in developing and implementing AO systems on Lick, Palomar and Keck Observatories. Several required capabilities are not currently available. Estimated costs for these components come from work with vendors on related development activities and other developers' estimates. Related work on several key areas by members of the CfAO also contributes to our estimates of likely costs for the AO systems. As noted before, there are many critical development issues for AO and the cost estimates for these are highly uncertain. It will be critical in Phase 2 to greatly strengthen the basis for estimates for the AO systems. We plan to fund AO at a fixed price, thus the actual performance or requirements are not sharply defined. This plan will be carefully revisited towards the end of Phase 2.

CELT Observatory Development

Work Breakdown Structure and Budget

(Real Year $K)

Cost Elements\Fiscal Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	TOTAL
O1.0 Project management	**1364**	**1243**	**1161**	**1444**	**1513**	**1787**	**2942**	**1924**	**1965**	**2088**	**1326**	**18756**
1.1 project manager	687	523	481	573	596	828	1706	791	838	877	511	8411
1.2 business operations	233	354	402	517	546	570	600	632	540	571	352	5316
1.3 information technology	388	308	218	289	304	319	488	346	363	380	253	3655
1.4 project scientist	55	58	60	64	68	71	75	79	83	88	52	752
1.5 public relations	0	0	0	0	0	0	73	76	142	173	158	622
O2.0 System architecture and analysis	**544**	**595**	**594**	**812**	**1029**	**1141**	**703**	**706**	**739**	**774**	**440**	**8077**
2.1 leadership	157	167	175	185	196	206	217	230	242	256	140	2170
2.2 preliminary design trade studies	101	100	105	0	0	0	0	0	0	0	0	306
2.3 systems engineering analysis	95	100	105	109	109	109	109	115	121	128	70	1171
2.4 optical installation and alignment engineering	191	228	209	517	724	826	376	362	376	390	230	4430
O3.0 Project engineering	**183**	**332**	**554**	**661**	**698**	**733**	**773**	**818**	**952**	**897**	**596**	**7195**
3.1 leadership	128	176	186	197	209	219	231	244	257	271	150	2268
3.2 system engineering	29	82	226	311	329	347	365	388	499	418	330	3323
3.3 quality/reliability/maintability engineering	27	74	142	152	160	167	176	186	196	207	116	1604
O4.0 Site acquisition	**2314**	**932**	**919**	**6464**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**10629**
4.1 lead engineering and equipment	1273	421	380	202	0	0	0	0	0	0	0	2275
4.2 evaluate candidate sites	598	45	48	0	0	0	0	0	0	0	0	690
4.3 evaluate site 1	111	117	123	0	0	0	0	0	0	0	0	350
4.4 evaluate site 2	111	117	123	0	0	0	0	0	0	0	0	350
4.5 evaluate site 3	111	117	123	0	0	0	0	0	0	0	0	350
4.6 evaluate site 4	111	117	123	0	0	0	0	0	0	0	0	350
4.7 site acquisition expenses	0	0	0	6262	0	0	0	0	0	0	0	6262
O5.0 Enclosure	**608**	**1751**	**1401**	**6348**	**16751**	**7566**	**6870**	**0**	**0**	**0**	**0**	**41295**
5.1 management and in-house engineering	0	132	175	186	196	207	100	0	0	0	0	995
5.2 conceptual design studies	608	408	0	0	0	0	0	0	0	0	0	1016
5.3 preliminary design contract	0	1211	1226	0	0	0	0	0	0	0	0	2437
5.4 final design/build contract	0	0	0	6162	15367	6140	5131	0	0	0	0	32800
5.5 furnishings	0	0	0	0	1189	1218	0	0	0	0	0	2407
5.6 refrigeration	0	0	0	0	0	0	1640	0	0	0	0	1640
O6.0 Telescope mount	**819**	**1720**	**2579**	**9562**	**11652**	**11739**	**3616**	**819**	**0**	**0**	**0**	**42506**
6.1 management and in-house engineering	130	351	474	656	692	651	344	0	0	0	0	3299
6.2 structure	409	839	1290	5509	6776	6945	712	0	0	0	0	22479
6.3 subcells	22	44	68	290	357	366	37	0	0	0	0	1183
6.4 drives and controls	86	177	272	696	1094	975	999	512	0	0	0	4810
6.5 mechanisms	43	88	136	464	475	487	500	205	0	0	0	2398
6.6 cluster testbed	22	0	0	557	594	609	624	0	0	0	0	2406
6.7 cabling	11	22	34	116	119	122	125	51	0	0	0	600
6.8 plumbing	11	22	34	116	119	122	125	51	0	0	0	600
6.9 bearings	43	88	136	580	713	731	75	0	0	0	0	2366
6.10 hydrostatic journals	43	88	136	580	713	731	75	0	0	0	0	2366
O7.0 Optics	**1657**	**1244**	**3191**	**11036**	**17761**	**13203**	**8650**	**5622**	**0**	**0**	**0**	**62363**
7.1 management and in-house engineering	189	357	521	463	481	500	527	250	0	0	0	3289
7.2 primary segments	1187	435	2139	7810	13809	10556	6935	4386	0	0	0	47256
7.3 secondary mirror	121	283	255	1603	2134	1539	875	664	0	0	0	7474
7.4 adaptive secondary mirror	33	0	0	0	0	0	0	0	0	0	0	33
7.5 tertiary mirror	125	169	276	1161	1337	608	314	322	0	0	0	4311
O8.0 Optics passive support	**543**	**690**	**451**	**1629**	**1867**	**1900**	**1431**	**632**	**0**	**0**	**0**	**9143**
8.1 management and lead engineering	33	45	47	46	49	51	54	27	0	0	0	353
8.2 primary mirror	356	394	223	1169	1198	1228	1259	519	0	0	0	6345

Figure 4-4a. Observatory Development Budget, page 1

CELT Observatory Development

Work Breakdown Structure and Budget

(Real Year $K)

Cost Elements\Fiscal Year	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**TOTAL**
8.3 secondary mirror	79	127	92	261	363	364	62	0	0	0	0	1348
8.4 adaptive secondary mirror	0	0	0	0	0	0	0	0	0	0	0	0
8.5 tertiary mirror	75	123	88	153	257	256	57	86	0	0	0	1096
O9.0 Optics active control	**1121**	**1075**	**924**	**4298**	**5189**	**5333**	**2799**	**2399**	**1442**	**547**	**560**	**25688**
9.1 management and lead engineering	162	240	326	347	367	387	408	240	252	0	0	2728
9.2 primary	522	656	425	3300	4051	4419	2109	1141	1190	547	560	18919
9.3 secondary	135	0	55	220	267	167	69	362	0	0	0	1276
9.4 adaptive secondary mirror	29	0	0	0	0	0	0	0	0	0	0	29
9.5 tertiary	185	0	82	329	400	252	102	543	0	0	0	1894
9.6 wavefront sensors (1/instrument) 2 assumed	87	180	37	102	105	108	110	113	0	0	0	842
O10.0 Adaptive optics	**6580**	**7540**	**7117**	**8819**	**17669**	**31179**	**23898**	**13593**	**13071**	**11044**	**8171**	**148681**
10.1 management and lead engineering	767	882	861	1005	1064	1115	1166	1233	1289	1256	1208	11846
10.2 component technology development	3582	3887	3647	179	37	0	0	0	0	0	0	11332
10.3 technology demonstration	2024	2430	2133	71	65	0	0	0	0	0	0	6722
10.4 Multi-conjugate AO (MCAO)	0	0	229	5243	11390	20307	17359	8724	8942	7532	4651	84376
10.5 Low Order AO (LOAO)	0	0	122	2322	5114	9758	5372	3637	2840	2256	2312	33733
10.6 Advanced system studies	207	341	124	0	0	0	0	0	0	0	0	672
O11.0 Facilities	**161**	**417**	**604**	**1369**	**6540**	**12479**	**5687**	**573**	**196**	**201**	**0**	**28225**
11.1 management and in-house engineering	0	132	175	186	196	206	0	0	0	0	0	895
11.2 summit facility	161	284	429	975	5237	5384	2946	573	196	201	0	16384
11.3 headquarters facility	0	0	0	208	1108	6889	2742	0	0	0	0	10946
O12.0 Software and related hardware	**683**	**1062**	**1628**	**1640**	**1908**	**1656**	**1433**	**1328**	**1303**	**1321**	**982**	**14943**
12.1 management and lead engineering	301	319	333	506	536	566	598	632	666	702	739	5899
12.2 telescope control	23	25	26	138	291	307	326	172	181	191	101	1781
12.3 primary mirror control)	0	0	0	0	0	0	0	0	0	0	0	0
12.4 optics alignment and phasing	0	0	0	0	0	0	0	0	0	0	0	0
12.5 facility control	23	25	26	34	73	77	81	43	45	0	0	427
12.6 instrument control	23	25	26	28	29	31	32	34	36	38	40	343
12.7 adaptive optics	0	0	0	0	0	0	0	0	0	0	0	0
12.8 laser systems	0	0	0	0	0	0	0	0	0	0	0	0
12.9 data management	46	49	53	70	73	154	245	258	181	192	101	1421
12.10 simulators	23	25	26	69	73	77	0	0	0	0	0	293
12.11 environmental monitoring	0	0	0	0	0	0	0	0	0	0	0	0
12.12 queue scheduling and remote observing	0	0	0	0	0	31	49	86	91	96	0	352
12.13 infrastructure	140	493	1037	692	731	310	0	0	0	0	0	3403
12.14 hardware	102	102	102	103	102	103	102	103	103	102	0	1023
O13.0 Observatory commissioning	**0**	**17**	**18**	**105**	**219**	**1275**	**2707**	**3353**	**3335**	**3394**	**1746**	**16169**
13.1 management and lead engineering	0	17	18	46	98	780	824	870	917	966	520	5055
13.2 summit	0	0	0	0	0	241	847	1204	1268	1340	710	5610
13.3 headquarters	0	0	0	59	121	254	1036	1280	1150	1087	516	5504
O14.0 Scientific Instrumentation Allocation	**2191**	**3671**	**4948**	**6379**	**8036**	**10765**	**12083**	**13236**	**11054**	**5904**	**0**	**78267**
14.1 management and in-house engineering	188	386	396	406	416	426	437	448	459	235	0	3799
14.2 Instrument #1 (Med To High Res spect)	1212	1987	3055	4610	5706	7310	7493	7681	4625	3127	0	46805
14.3 Instrument #2 (CELT fiber Positioner)	188	294	388	390	499	896	1093	1344	1561	659	0	7312
14.4 Instrument #3 (AO, NIR IFU spectrograph and imager)	603	1004	1109	974	1415	2132	3060	3763	4409	1883	0	20352
Reserve	**2143**	**3019**	**4743**	**15172**	**23111**	**20902**	**14455**	**7520**	**2609**	**2198**	**1392**	**97264**
Observatory development total	**20911**	**25308**	**30831**	**75738**	**113943**	**121655**	**88047**	**52522**	**36665**	**28366**	**15213**	**609201**

Figure 4-4b. Observatory Development Budget, page 2

Science Instruments

Science instrument costs are based on estimates from the engineering staff of UC and Caltech Observatories. Their estimates are based on the conceptual design studies for specific instruments. These costs are only indicative, since the actual instruments for CELT have not been selected. Science instruments will be developed at a fixed price, since the actual instruments and the Level 1 requirements for them have not been established. Selecting the desired instruments and producing preliminary designs with accurate costs will be an essential activity during Phase 2. Near the end of Phase 2 we will carefully review the funding and implementation plan for science instruments.

Facilities

Costs are based on scaling up costs for Keck Observatory to the facility size needed for CELT.

Software and Related Hardware

Costs are based on an estimate of the required software activities by the manager of Keck Observatory software, Hilton Lewis, and by Al Conrad, also at Keck Observatory. Opinions about cost of software vary significantly based on individual experience and assumed development process. In general, earlier software development will result in lower operations costs.

Observatory Commissioning

Cost of commissioning is based on significant experience with the commissioning of Keck, including telescope alignment, segment surveying, installation and alignment and secondary and tertiary installation and alignment.

4.7.2 Workforce

The workforce profile for the CDP budget is shown in Table 4-2. This is extracted from the bottom-up estimates of each WBS element that contains in-house CELT work force.

4.7.3 Reserve

Since scientific instruments and adaptive optics are cost-capped, no explicit reserve has been allocated to them. A reserve of 34% for items other than instruments and adaptive optics is included in this budget. This reserve allocation is based on a bottom-up analysis of uncertainty at the time of project start. A qualitatively determined uncertainty ranging from 5% to 100% has been assigned to each element of the WBS, at least down to Level 2. A reserve has then been calculated for each item. These have been added algebraically to arrive at a total reserve for each year of the project. Reserve requirements will be regularly assessed during Phase 2 and adjusted at the end of Phase 2 to reflect progress achieved in mitigating perceived risks.

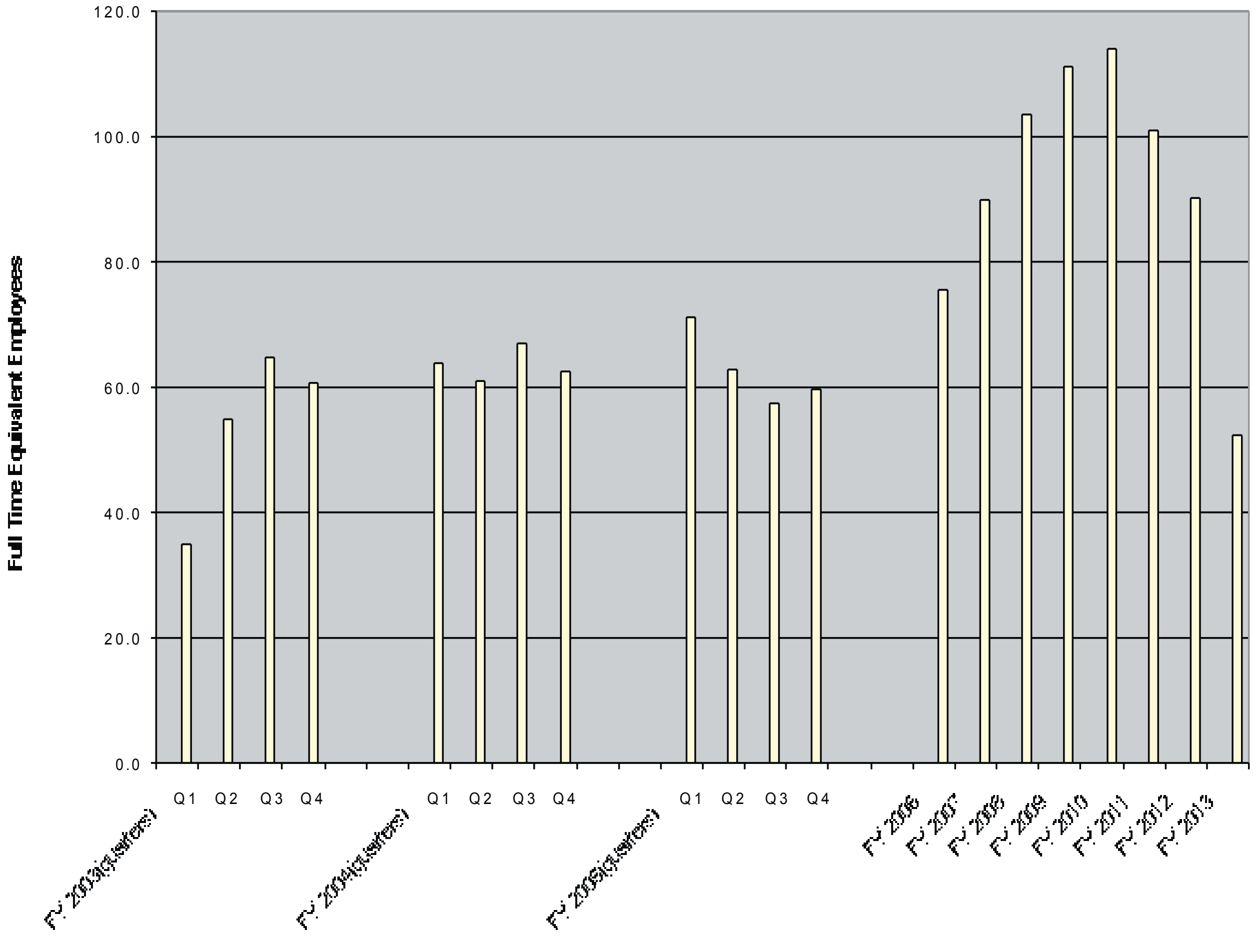

Table 4-2.Workforce.

Chapter 5. Science Oversight Plan

Science guidance to the project will be given through two channels. The Science Advisory Committee (SAC) will provide input from the broad community of astronomers at the California Institute of Technology and the University of California. The SAC will meet quarterly and provide its input on that time scale. The Project Scientist will provide individualized input to the Project Manager on a day-to-day time scale. Although different in their perspectives and time scales, the goal of both of these channels is to ensure that the telescope, instruments, and adaptive optics capabilities meet the needs of the user community as embodied by the Level 1 requirements. They also provide input to the Project Manager concerning cost-performance tradeoffs to maximize scientific utility of the observatory.

Both the SAC and the Project Scientist will continue to be active in the Operations Phase.

5.1 Science Advisory Committee

The Science Advisory Committee will be a committee of scientists composed of a co-chair from UC, a co-chair from Caltech, three additional members from each of the two institutions, the director of UCO/Lick, the director of the Caltech Optical Observatories, and the Project Scientist. The CDC Board of Directors will appoint the SAC members and Project Scientist.

The SAC will meet quarterly and on an ad hoc basis. At these meetings the Project Manager, Project Scientist, Instrument Project Manager, AO Project Manager and, when appropriate, Chairs of Working Groups will provide status reports. The SAC Co-Chairs will attend Board meetings, report on their assessment of the process and status of establishing and meeting the requirements, and make recommendations on all issues pertaining to the science capabilities of the observatory.

The SAC will have a budget to commission small studies and for travel. This budget is shown in Figure 3-3.

With the Project Manager, the SAC will establish working groups to evaluate specific issues. Some of these working groups may be continuations of the working groups established in Phase 1, the Conceptual Design phase. These include

- Telescope Working Group
- Telescope Enclosure Working Group
- Scientific Instruments Working Group
- Adaptive Optics Working Group
- Science Working Group
- Site Working Group

The SAC responsibilities will be

1. Establish the performance requirements for the telescope, instruments, and AO systems jointly with the Project Manager and Project Scientist. The SAC must approve all changes to Level 1 requirements.
2. Establish the science capabilities vision for the observatory.
3. Provide the user community a means of giving input into observatory planning and eventual operations and to solicit such input.

4. Work with the PM during development and construction phases, to reevaluate requirements when budget/schedule/performance trade-offs must be considered.
5. Solicit proposals for and select instruments jointly with the PM.
6. Review the AO plans and select the AO systems to be built.
7. Recommend a site for the CELT observatory to the CDC, in consultation with the PM.

5.2 Project Scientist (PS)

The Project Scientist will interact daily with the Project Manager. He or she will require a detailed knowledge of the science requirements, the error budgets, and the technical compromises used to achieve those budgets.

With the SAC the Project Scientist will develop the observatory requirements and goals. The PS will assist in developing, clarifying and interpreting the Level 1 requirements, but the SAC is the approval body, along with the PM.

While ensuring the science requirements are being implemented in the observatory design and construction, the Project Scientist will assist the Project Manager in dealing with day-to-day engineering and technology issues.

The Project Scientist must attend the SAC meetings and represent the SAC on a daily basis to the Project Manager.

The budget for the Project Scientist is contained within the CDP management budget (WBS 1.4).

Chapter 6. Operations Plan

6.1 Introduction

The optimum operating model for CELT will be highly dependent on the assumed site, the mode of scientific and technical operations, and how the various components of the observatory interrelate and interface with the external astronomical user community. In this chapter each of these issues is explored in the context of major decisions that will need to be made during the preliminary design phase. A baseline "stand-alone" model has been determined following experience gained from the partnership's operation of the Keck Observatory over the past decade. However, it is recognized that much will depend on how CELT is to be optimally exploited scientifically as well as on the observational methods of 2010; and the extent to which operations could be merged with those of the Keck observatory if CELT is placed on Mauna Kea.

6.2 Issues Relating to the Site

The process of selecting a site is described in Chapter 13 of Volume 1. There are three main selection criteria for optical/infrared telescopes: the fraction of clear nights, the amount of distortion introduced by the earth's atmosphere ("seeing"), and the transparency of the earth's atmosphere at infrared wavelengths. Other important astronomical considerations include access to various celestial objects, wind conditions, and temperature stability during the night. Economic considerations include accessibility, host partner arrangements, and political issues (particularly for overseas locations).

According to these criteria, the best-known world sites are in northern Chile and on Mauna Kea in Hawaii. These sites offer a high percentage of clear nights and excellent seeing. We are also examining the possibilities in North America, should neither Chile nor Mauna Kea be viable options for political or practical reasons. From a scientific point of view, it is still premature to make a site decision, and we are planning on an extensive site testing and evaluation program (cf. Chapter 13, Volume 1).

The science criteria will be the main drivers in the final site selection. However, given a close choice between two or more alternatives, political and practical issues, including the ease of construction and operation, may become decisive. For example, there are operational advantages in placing CELT on Mauna Kea, assuming that the available site is scientifically competitive. As the CELT partnership is modeled on that for the Keck observatory, so the existing California Association for Research in Astronomy (CARA) infrastructure could be utilized to great effect. CARA staff with experience in operations would become available for hire and perhaps a joint operational model would evolve with obvious economies of scale. Inter-observatory synergies have worked well in similar situations, e.g., the Mauna Kea Joint Astronomy Center operated by the UK, Canada, and Netherlands.

If the selected site is in Chile (or perhaps Mexico), some synergy with other observatories and institutions there may be possible. A site outside the US will involve international discussions with host organizations, operational expenditures subject to fluctuating exchange rates, and progress potentially hindered by import and export issues. Most likely an additional layer of management would be necessary in both the United States and overseas offices in order to deal with foreign matters.

Operating two distinct observatories (Keck and CELT) separated by a great distance would benefit neither, but may well be necessary if sites significantly superior to Mauna Kea are found elsewhere, or if building CELT on Mauna Kea is not possible or practical for other reasons. A good example of the challenges faced in such a configuration can be seen at first hand with the Gemini project (which operates two identical telescopes in Mauna Kea and Chile). Gemini's experience in the next two years should be considered carefully before deciding to site a large telescope in Chile. Likewise, experiences of the LMT observatory will be relevant when considering sites in Mexico.

The feasibility of hiring good engineers and support/instrument scientists is also an important issue. It is currently very difficult to compete with salaries in high-tech industries, and the promise of a challenging job at a less competitive salary may not be sufficient. Chile and Hawaii are remote locations for talented staff with high associated travel costs. Pleasant working conditions, the proximity of good schools, and generous annual leave entitlements are increasingly determining which observatories recruit the best staff. It is not clear which of Chile or Hawaii has the advantage. Similar considerations also apply to possible sites in the remote areas of the US southwest and northern Mexico. Ensuring a motivated staff is a most important consideration for the Operation Phase.

6.3 Operational Components

Prior to the construction phase, the Project Office will be located in California. However, when construction begins, it is logical to move all engineering activities and site procurement officers to a site headquarters (HQ) located closer to the observatory. As the project nears completion, the function of the HQ will naturally evolve into that of observatory maintenance and observing support. Logistics and the provision of adequate working conditions will almost certainly mean such a HQ will be at a convenient town within a few hours' reach of the telescope (summit), the only realistic location where certain operational activities can be performed.

The telescope enclosure is a major cost item, discussed in Chapter 12 of Volume 1. An associated building is also necessary to support the summit operations staff. We estimate this building will serve around 40 daytime and no less than 4 nighttime employees (see below). The facilities contained within the enclosure and its associated building will be similar to those available at the Keck observatory. These will include equipment and personnel support required for telescope maintenance (bearings, drives, etc.); mirror cleaning and coating (including segment exchanges); instrument support and maintenance; optics handling; thermal control of the enclosure environment; dome and shutter control; and telescope control.

The site HQ provides administrative, engineering, and technical oversight for all summit activities. In the case of the Keck Observatory, the HQ also provides support for visiting astronomers and a remote observing facility. Its staff also ensures that externally produced instruments are delivered and documented to the standards necessary for successful maintenance and user support.

In the spirit of the broad and far-reaching astronomical research to be carried out with CELT by the academic faculty of UC and CIT, we fully recognize the importance and need for extensive public relations and public outreach. Independent of the staff required for professional scientific support, we intend to have a minimum of one FTE included in the steady-state budget for public relations and outreach. This person will be responsible for a wide range of activities including organization of press releases in conjunction with the press offices of CIT and the UC campuses; web site development; public and press visibility; K-12 education program; creation of advertising materials such as posters and slide sets; and organization of special site visits.

As communication networks continually improve, the traditional model of a self-contained observatory with an on-site Director and a full complement of technical staff supporting a stream of visiting astronomers is being discarded. The Keck observatory was among the first to permit astronomical observations to be conducted from the site HQ (and later California) rather than from the summit. Our CELT operational model anticipates this continuing trend, not only for the astronomical use of the telescope, but also for software and hardware support.

It is unclear the extent to which it is scientifically useful or cost-effective to continue this trend towards remote operations. There is a natural tension between the obvious need for astronomers to maintain close contact with resident observatory staff and the convenience and economy afforded by a completely remote operational model. At this stage it would be foolhardy to adopt a rigid stance on this issue given the technical complexity of CELT. However, it is wise in our view to begin investing in the necessary infrastructure for both astronomers and technical support staff to conduct their business from California.

Adequate communication channels will thus be required to make effective and efficient use of the telescope. These channels, to both the site HQ and the summit, will permit observers to routinely collect data from observing stations in California. They will also enable the real-time monitoring of the performance of the telescope and its instruments. We envisage that engineering tests, diagnoses and software repairs can all be conducted remotely. A key issue is the extent to which the CELT partnership wishes to invest in remote leadership, e.g., whether the CELT Director is located at the site HQ facility or at a possible California operations center (see Section 6.6). Clearly the degree to which remote management is implemented would have a significant impact on costs.

Communication channels can readily support high-speed networking and point-to-point video-conferencing with high quality audio. A high-bandwidth network (> 45 Mbs) will support effective interactive on-line collaboration between remote observers and staff at the site HQ and summit. There also must be an effective backup network path to protect against outages of the primary network.

Computers will play a critical role in all phases of observatory operation. The networks at the summit, the HQ, and California remote stations must have a very high degree of reliability, be easily maintained, and be able to communicate with one another effectively. Given the rate of progress in technology, it is premature to specify the details. A great deal of experience with similar computer networks has been obtained at the Keck Observatory.

6.4 Science Considerations

The CELT telescope will be designed to achieve ambitious science goals. Most of the science programs will require exquisite observing conditions including photometric clarity, infrared transparency or good seeing. However, these will not occur simultaneously. The cost and complexity of CELT will demand that the observational efficiency is high, and that observing programs are optimally matched to the current observing conditions.

How to optimize the match between the telescope environment and the science requirements of a particular program remains a controversial question in the astronomical community. Flexible scheduling, where time is allocated to individuals according to a rank-ordered list consistent with the weather at the time, has been attempted on a number of telescopes with only limited success. This mode places an additional responsibility on resident staff. On the other hand, the traditional mode of scheduled observing where nights are allocated to individuals months in advance, while administratively convenient and consistent with freedom of choice, cannot be regarded as the most efficient model. This mode cannot easily respond to sudden changes in observing conditions, sudden changes in instrument performance, or time-sensitive astronomical events.

During the preliminary design phase strategies for remote-observing and flexible scheduling will be examined in detail. Scripted observing has been implemented at several telescopes already and should be carefully considered for CELT. An important prerequisite for any form of acceptable flexible scheduling is an accurate model for how the telescope and instrument combination performs in a given situation. Such "active" performance predictors will be an important extension of the current documentation available to observers and support staff charged with coordinating the observers. Linking this to the increasingly reliable weather prediction system will be highly advantageous.

A final issue is the manpower associated with data logging, reduction, calibration, and the archive. Although data reduction pipeline tools are logically the province of the instrument teams, their continued support and maintenance inevitably falls on observatory staff. The archive serves two purposes: as a backup of data obtained by CELT, and as a database for future scientific studies. To be useful, the archive must have an indexed log. Even if users do not have access to all archived data, it will still be essential to have an accessible observatory log.

The above issues have significant operation implications. They also will impact the decision regarding where the Director should be located. A significant component of flexible scheduling can be used to argue for a strong intellectual presence in a California-based operations center. As with all facilities, the support and maintenance of data pipeline tools and an archive are also activities best located alongside active researchers. In view of this, it is important to explore the consequences of considering CELT ultimately as a remotely operated telescope, technically maintained by trained engineers led by a on-site superintendent and with intellectual leadership based centrally in the astronomical community.

6.5 A Baseline Operational Model

With so much uncertainty in both the geographical location of CELT and the observing philosophy, it is premature to make detailed plans for all aspects of observatory operation. Thus, our current strategy is to first cost a baseline operational model, and to then briefly assess the key uncertainties that must be addressed during the preliminary design phase, prior to the production of a reliable manpower and operational plan.

Labor is the dominant cost in the annual operations budget of a large telescope and CELT will be no exception. The baseline model is drawn foremost from a decade's experience of operating the Keck Observatory. This assumes CELT will be operating in a "stand-alone" fashion; possible synergies by operating alongside other telescopes are not considered at this stage.

Quite apart from the logistic issues discussed earlier, there are specific features of CELT that make its operation more complex than that of the Keck observatory. In hardware terms, these include the routine use of lasers, maintaining the performance of 1080 primary mirror segments, and assisting in the installation and commissioning of instruments of an unprecedented scale and sophistication. In addition, experience with Keck has shown the dangers of having an insufficient manpower contingency for routine maintenance items associated with the telescope, enclosure, various aspects of telescope control and instrument software, and a rudimentary data archive.

6.5.1 Summit Activities

At Keck, 30-40 daytime and 4 nighttime summit personnel are responsible for maintenance of the telescope, keeping it at peak performance level for every night of observation. This includes general maintenance of the dome, telescope, scientific instruments and the supporting infrastructure. Like most major research facilities, CELT is composed of many subsystems, all of which must work in concert to deliver the predicted image quality. While computer-aided prediction techniques have been developed at various observatories, the responsibility of ensuring the telescope is in the optimum condition must always be that of a single individual.

The summit crew, following suitable instructions from any location (the site HQ or a California center), can perform the installation and straightforward modification and repair of astronomical instruments. Accordingly, we envisage the summit operations as largely self-contained. A number of other operations such as mirror cleaning, mirror re-coating, instrument performance verification, etc., will also be the responsibility of the summit day crew.

The night crew is responsible for operating the telescope during observing, monitoring telescope performance, and monitoring the weather conditions at all times to be alert for changes or problems. A shift working pattern is essential for these night employees so that during their day shifts they gain necessary technical experience in order to distribute their nighttime experiences directly to those responsible for technical upgrades and maintenance.

In comparison to the current Keck operations (after allowance for the fact that CELT is a single telescope), we have increased the size of both day and night crews to allow for enhanced maintenance, routine laser operation and the greater complexity of the instrumentation. For CELT we estimate day and night crews of around 27 and 11 respectively.

6.5.2 Site Headquarters

The Keck HQ houses approximately 80 people, including those who visit the summit each day. Although highly =regarded as a successful world-class observatory, Keck is without question a very lean operation in comparison with many other international facilities. Some of these distinctions represent important differences in the entire philosophy of how astronomers are expected to observe (see below).

In the present Keck model, the HQ staff comprises instrument scientists; mechanical, electronics, and optical engineers; computer software and support personnel; technicians; and administrative staff for human resources, purchasing, and accounting. This staff, working with summit personnel as well as with California scientists, is responsible for the overall operation of the observatory as a world-class scientific research facility.

We consider it essential to include some additions to this model, *regardless of the issues raised in the next section*. One is a staff complement responsible for rudimentary archiving and distributing data to remote PIs. The second is an increased component of observer and instrument support necessary to maintain a good understanding of the real-time performance model of the telescope and its instrumentation. Without these investments, it will never be possible retrospectively to activate anything other than the present, traditional modes of operation.

Further enhancements to the basic Keck model are also discussed in the next section. Unlike the situation for the summit operations, the labor model for the HQ depends critically on the existence of a California operations center.

Table 6-1. **Baseline Model:** Steady-State Staffing for Site Headquarters and Summit.

	SITE HQ	SUMMIT DAY	SUMMIT NIGHT
Director	1		
Deputy Director	1		
Administrative Director	1		
Human Resources	3		
Purchasing	3		
Travel	1		
Accounting	2		
Clerical	4		
Administrative Assistant		1	
Public Relations	1		
Chief Engineer	1		
Group Managers (*)	8		
Safety Officer	1		
Mountain Supervisor		1	
Optics Group	6		
Software	6	3	
Computer System Administration	2		
Electronic Engineers	2	1	
Electronic Technicians	4	3	
Mechanical Engineers	3	1	
Mechanical Technicians	5	3	
Instrument Scientists (2/instrument)	6		
Instrument Specialists		3	
Observer Support/Communication	5		
Archive (documents/web)	1		
Archive data	3		
Maintenance		6	
Optical Technician		1	
Adaptive Optics (elec., mech., software)	7		
Laser Engineer		1	
Adaptive Optics/Laser Support		3	3
Telescope Operators			4
Telescope/Instrument technicians			4
Totals =	77	27	11
Total personnel =	115		

* Groups:
computing, electronics, mechanical engineering, telescope optics,
adaptive optics, instrumentation, data archive/processing, user support

6.6 Key Issues

We now summarize the principal uncertainties that must be resolved during the preliminary design phase. The outcome of each of these is likely to significantly affect the cost of the baseline model.

6.6.1 A California Operations Center

CELT is likely to cost a significant fraction of a major space mission, and we have argued that it is important to consider operations with an open mind. The logical outcome of recent trends in remote and scripted observing would be to house the operations center in an academic environment with a leading astronomer as Director, perhaps alongside the archive, ensuring excellent communications with the Californian astronomical community.

During the preliminary design phase, careful consideration will be given to an alternative model wherein some subset (possibly a large component of the above 77 staff) is normally based with the Director in California, undertaking *tours of duty* to the site HQ during times of great activity. Such periods would include the initial commissioning of the telescope, the delivery of each major instrument and periodically according to the plans of the Director. A number of observatories operate in this mode including Carnegie and, on a grander scale, ESO.

There are clearly some negatives in operating a remote observatory from California. These include non-standard working arrangements for many skilled staff who have to consider moving for extended periods on occasion; establishing engineering priorities that are ranked according to scientific needs from a distance; and maintaining good morale between two disconnected teams. Such a model might also be more expensive.

Associated with this important decision are the scientific implications of operating a remote telescope. Can those in California responsible for user support remain adequately in touch with technical staff that maintains day-to-day contact with the instruments and telescopes?

6.6.2 Synergy with CARA

Some of the disadvantages of a remotely operated telescope might be overcome if, ultimately, the Keck telescopes were also operated in this manner. Assuming this is practical for the Keck telescopes and CELT is placed on Mauna Kea, the existing infrastructure in Hawaii could form the basis of an adequate HQ for a remote outstation.

The increased infrastructure cost associated with managing two locations (California base plus a Hawaii site HQ) would be significantly offset by establishing a strong synergy between the two observatories. In previous cases where operations were merged across two telescopes on the same site (Isaac Newton plus William Herschel telescopes at La Palma, UKIRT and JCMT at the Joint Astronomy Center, Hawaii) savings of 20-25% over a “stand-alone” model were realized. Such savings could apply to the staffing figures at the site HQ and the California base.

It is interesting to speculate on the effect that such a California base would have on the partners’ existing California telescopes, Lick and Palomar. Caltech and UC, by entering a second partnership, have the opportunity to consider jointly managing, through a single base, *all* of their respective telescopes. There could be many challenges in implementing such an approach, given the responsibilities of each institution to its own faculty and students. Therefore, it may be worth considering whether a more cohesive and coordinated mode of operation for CELT and the two institutions could be developed to make further operational savings.

6.6.3 Chilean Operations

In the case of a CELT sited in Chile, the degree of synergy possible with CARA would be very limited. It is doubtful whether any significant site-based operational savings would accrue even if CELT and Keck adopted similar procedures and technological standards. In the case of a remotely operated telescope, a Californian base could still act as the user interface to two distributed observatories.

In summary, we envisage a significant increase in operating CELT in Chile. The manpower differential could be as great as 20% depending on whether Keck and CELT operations are to be merged and whether there is a California base.

6.7 Facilities Budget and Other Costs

A regrettable feature of many world-class observatories in current operation is the inadequate planning that went into establishing an ongoing facilities budget for telescope, instrument and detector upgrades, and later generations of instrumentation. It seems prudent to address this issue now. We thus recommend that a budget be clearly established for these needs, and the Director should control it based upon advice from a Scientific Advisory Committee composed of both users and instrument builders.

We suggest the following guidelines are necessary to maintain a healthy observatory:

1. The development program should be science driven, and ideas should be sought regularly by open competition from the community.
2. The observatory staff should build no major instruments. Instead, instruments should be built by partnerships of academic groups and industry, with the observatory staff playing a key interface role. This is more likely to be successful if the center of activity is in California and managed by a designated individual.
3. A reward scheme should be implemented for instrument builders and their science teams.

In Chapter 10 of Volume 1, we describe an instrument plan whose capital cost exceeds \$100M, thus it seems sensible to budget for a steady state instrument and detector fund of about \$10-15M per annum.

In addition to an ongoing instrumentation fund, the operations budget should include annual appropriations for two additional areas where continual developmental activity is important: adaptive optics (\$3M/yr) and facility advances (\$2M/yr). Adaptive optics is likely to remain in a state of continual development and advancement for decades to come, and it is extremely important that CELT be equipped with the most powerful and effective adaptive optics systems available. Adaptive optics will be a crucially important component of the scientific performance of the telescope. In addition, the technology affecting the overall performance and effectiveness of the telescope and its associated systems and components is also expected to advance continually over time. Sufficient funds to develop and incorporate this evolving technology are important for maintaining CELT at the forefront. The budgetary amounts suggested for these developmental programs are based on current estimates, and they will be critically examined further in the next phase of the project.

Finally, non-payroll costs include support of user and advisory committees, the CELT Board and standard overheads. There may be significant additional expenses (legal and otherwise) concerned with operating in a foreign country like Chile.

6.8 Summary

The table below combines the various discussions in the preceding sections and attempts to estimate, modulo the many uncertainties and outstanding issues, the overall cost of operating CELT on Mauna Kea alongside Keck, and in Chile, as a stand-alone operation. In deriving these costs, a total staff cost (including benefits and associated infrastructure) of $100K per FTE has been assumed for both locations (as advised by the Gemini project). All figures relate to year 2000 dollars. The above estimates are very approximate. More accurate and detailed analysis will be carried out in Phase 2.

Table 6-2. Estimated Total Operating Costs ($M, year 2000 $)

	Mauna Kea (alongside Keck)	Chile (stand--alone)
Stand alone operations (115 FTE)	11.0	11.0
CARA synergy (20%)	–2.3	
Management	0.5	0.8
Instrumentation	15.0	15.0
AO	3.0	3.0
Facilities	2.0	2.0
Total	29.2	31.8

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Appendix 1. Adaptive Optics Development Plan

A1.1 Introduction

This appendix describes the plan to provide adaptive optics capability to the observatory. This includes all necessary theoretical and simulation work, component technology development, and feasibility demonstrations that are required to address this challenging yet crucial element of the observatory.

The goals for adaptive optics development in Phase 2 of the CELT project are:

- Develop detailed near-infrared and mid-infrared adaptive optics system architectures that cost-effectively satisfy the CELT science requirements
- Develop key subsystem component technologies through industrial and community partnerships (lasers, deformable mirrors, low noise cameras)
- Reduce AO performance and cost risk through laboratory and field validation of key architectural concepts, including multiple laser guide star wavefront sensing and multi-conjugate correction
- Develop a detailed management plan for observatory adaptive optics subsystem development

Despite the potential advantages, not all observations can be made with adaptive optics. Some projects require a field-of-view greater than that afforded by any practical adaptive optics system. Other observations are of resolved objects, or are not background-noise-limited, reducing the AO SNR and resolution advantages. Still, the science case for CELT (Preliminary Design Plan Volume 1, Chapter 2) is weighted heavily toward observations that do benefit from adaptive optics (see also Volume 1, Chapter 9).

A1.2 Key challenges for CELT Adaptive Optics

There are powerful scientific advantages that can be gained from diffraction-limited observations on large telescopes; however, the field of adaptive optics remains in its infancy. Although all existing major observatories have or are planning adaptive optics systems, they remained scientifically limited by the absence of a sufficiently bright source of light with which to measure the instantaneous effects of the Earth's atmosphere. The natural sky provides many appropriate guide stars, but they are widely distributed on the sky, so that less than 1% of the sky is typically available for AO correction using natural guide stars (NGSs). The use of synthetic laser guide stars (LGSs) promises to dramatically increase the utility of adaptive optics, making a much larger fraction of the sky available to diffraction-limited observations. The use of such beacons is only beginning at astronomical observatories, but already astronomers have strong interest and expectations for this approach.

For a telescope of CELT's diameter, adaptive optics is even less mature. Unlike other CELT subsystems, the basic theoretical development of LGS based adaptive optics for a 30m diameter telescope remains incomplete. Certain scaling laws remain unknown; others may not scale predictably to CELT's diameter. The analytical and simulation tools required to investigate these issues, initiated in the conceptual design phase, remain immature. For giant telescopes the finite distance to the artificial star (Na layer height of 90 km) and the finite thickness of the Na layer (~10 km) are critical complications to the AO design. However, solving this problem with the tomographic use of multiple LGS may also allow us to easily increase the field of view with diffraction limited images, a very significant advantage. Aside from system design issues, there are specific technology challenges, directly related to CELT's large size that must be met. In at least three major areas, the required component technologies do not yet exist. High-actuator count deformable mirrors; high-power, appropriate format guide star lasers; and low-noise, fast-frame visible and near-infrared detectors all require advancement of the state-of-the-art to meet CELT requirements. For mid-IR optimized work, undemonstrated cryogenic deformable mirrors are required.

New controls, architectures, and algorithms are required to meet the real-time computing challenges. The overall complexity of software for CELT AO is likely to be significantly higher than that of existing AO systems. In some cases existing prototypical components will need to be re-engineered for improved reliability suitable for the summit environment.

Despite these challenges, it is our conviction that *adaptive optics for CELT is feasible and worthy of significant investment* as a fraction of the total observatory cost. We reach this conclusion through our development of a conceptual design (presented in Volume 1, Chapter 9) that suffers no fundamental limitation to achieving diffraction-limited science across the near-infrared observing band. However, to achieve these capabilities we must pursue a rigorous development plan for adaptive optics that creates confidence in the economic and practical feasibility of CELT AO.

A1.3 Development Plan

The challenges of developing the technologies and systems needed for CELT adaptive optics will be met by dividing the tasks into manageable technology development work packages, with clear development milestones and technology decision points. This will require working with industry, other astronomical observatories, and other AO technical programs, in addition to in-house efforts.

A1.3.1 Functional Requirements

The requirements for AO are summarized in Volume One, Chapter 3, and are given in more detail in CELT Report # 13 (Nelson, 2001). The telescope is expected to have two AO systems, one optimized for near-infrared (1-2.5 μm) science and the other for mid-infrared (3.4-20 μm) science.

A1.3.2 Architecture Definition

The adaptive optics system architecture is the high-level description of the subsystem functional definitions and the description of interactions between the subsystems. Although Volume 1 contains an illustrative design for a near-infrared (NIR) AO system meeting the CELT requirements, the actual selection of an AO system architecture has not occurred. In fact, the refinement of the NIR AO system is the primary goal of adaptive optics development in Phase 2.

In order to accelerate AO progress, we propose development in three interrelated areas: theoretical and simulation development, component technology development, and lab and field demonstrations. To meet the proposed CELT schedule, we are required to begin these efforts simultaneously, making certain decisions before all the necessary information is available from coordinated efforts. This form of concurrent engineering calls for a modular architecture with increasing levels of subsystem refinement as additional information becomes available.

A1.3.3 Theory and simulation development

The theoretical development of limiting wavefront errors (following, i.e., the formalism Sasiela, Electromagnetic Wave Propagation in Turbulence, Springer-Verlag 1994) and development of scaling laws for each wavefront error will occur in consideration of each of the following error terms, but is not limited to them.

- Wavefront error vs. total number of LGS photons
- Wavefront error vs. number and distribution of LGS asterism
- Wavefront error vs. asterism distortion for multiple LGS
- Wavefront error vs. number and distribution of NGS to solve tilt anisoplanatism
- Wavefront error vs. number and distribution of Rayleigh LGS to solve tilt anisoplanatism)

Each of these issues may require development of dedicated covariance or special numerical integration software.

Similarly, many issues for CELT adaptive optics will not yield to theoretical closed-form solution. In these cases, and to conduct detailed performance trade studies for subsystem technology choices, a high-speed, parallelizable Monte Carlo system simulation will be developed. This will address each of (but is not limited to) the following questions:

- What is the impact of the finite Na layer thickness?
- What is the impact of focal anisoplanatism of LGS within Shack-Hartmann wavefront sensors?
- What is the impact of tilt anisoplanatism of LGS within Shack-Hartmann wavefront sensors?
- What is the optimal reconstructor (trade study) for the combination of NGS and Rayleigh LGS to overcome residual Na LGS tilt anisoplanatism?
- How do fluctuations in the three-dimensional distribution of turbulence ($C_n^2(h,t)$) affect the closed-loop performance?
- What is the value (and the functional requirements) of $C_n^2(h,t)$ monitoring equipment? How is this information optimally integrated into the servo algorithm (trade study)?
- What is the tolerance on deformable mirror to wavefront sensor misregistration within an MCAO system?
- What is the relative value of uplink Na laser adaptive correction vs. increase laser power delivered to a seeing-limited spot (trade study)?
- What is the impact of high-temporal-frequency primary mirror segment vibrations on image quality?

The Monte Carlo simulation code will be scalable to operate on both desktop workstations and on high-performance clusters (e.g., Sun networks or the Beowulf system at Caltech's Center for Advanced Computing Research) and dedicated multiprocessor platforms (e.g., the supercomputers at LLNL or the San Diego Supercomputing Center).

A1.3.4 Component Technology Development

CELT AO will require advancement or refinement of the state-of-the-art for several key technology components. The development strategy will be to fund a small number of candidate approaches that are judged capable of meeting CELT requirements in each of these technologies, culminating in a set of technology downselects based upon vendor performance and cost predictions for the final system.

In order to give the most promising technologies sufficient opportunity to advance, we expect to make preliminary downselects to a small number of approaches, usually only two alternatives, but then invest in these programs early and consistently until the final downselect date.

The following table summarizes the technology development environment, and the tentative downselect date:

Component	**Some alternative technologies**	**Est. technology downselect date**
Deformable mirror	Electrostrictive arrays (Xinetics, Inc.), MEMS (Boston Micromachines, others)	9/04
Visible wavefront sensor detector array	CCD arrays (Marconi, Lincoln Labs), Hi-Visi arrays (Rockwell Scientific)	10/06
IR wavefront sensor detector array	HgCdTe arrays (Rockwell Scientific), InSb arrays (Boeing)	11/06
Na guide star laser	Sum frequency slab Nd:Yag (U Chicago/ Lite Cycles, CTI), Dye lasers (LLNL), Erbium doped fiber lasers (LLNL)	6/06
Rayleigh guide star Laser (if needed)	361nm tripled Nd:Yag and Nd:YLF (Coherent, others)	7/07
Real-time computer	DSPs (TI), General purpose processors (Intel, others)	11/07

Partnerships

CELT AO development will occur in an environment of continuing AO development on existing telescopes; parallel development of European and other extremely large telescope projects; the NSF-funded Center for Adaptive Optics (CfAO), headquartered at UC Santa Cruz; and the development of large deformable mirrors for space-based applications. A close, collaborative relationship with the following potential partners will increase the leverage of CELT investments and will be actively pursued:

CARA	Laser guide star AO development at Keck Observatory
CfAO	Theoretical and simulation development, laser development
ESO	Multi-conjugate AO Demonstrator (MAD) for the Very Large Telescope (VLT) Observatory
Gemini	MCAO system development, laser development
LLNL	LGS AO, laser development
MPIA (Heidelberg)	3-D model turbulence generator
JPL	High actuator count deformable mirror development
Padova	Pyramid wavefront sensor development
U of Arizona	Wavefront sensor development, AO for the Large Binocular Telescope (LBT)
UC Berkeley	MEMS development, high count deformable mirrors
U of Chicago	Laser development, reconstructor algorithms
U of Illinois	Rayleigh beacon AO at Mt. Wilson Observatory (MWO)
USAF	Starfire Optical Range, laser development

The most promising development area for collaborative development is likely to be in the area of guide star lasers, as nearly all existing telescopes will benefit from improved laser maturity. The CELT 2003-

2006 AO development budget for laser development (est. $3M) assumes significant cost sharing with collaborating institutions.

CELT will actively pursue partnering relationships to ensure specific progress in areas that are crucial to the science return of the observatory. Thus, we plan to invest in deformable mirrors, lasers, and wavefront sensors at a level sufficient to meet our performance goals, while seeking partnerships to reduce total cost and/or accelerate the schedule. This is particularly true for guide star laser development, where a failure of the community to collaboratively advance laser technology would likely result in significant cost risk to CELT.

A1.3.5 Laboratory and Field Demonstrations

Several fundamental aspects of CELT adaptive optics (such as the use of multiple guide stars) have never been attempted in an astronomical setting (although certain military experiments in the 1980's may have yielded preliminary investigations). It is therefore essential that CELT analytical work and the component technology development be validated with real-time, on-sky demonstrations of the key elements of the CELT AO architecture.

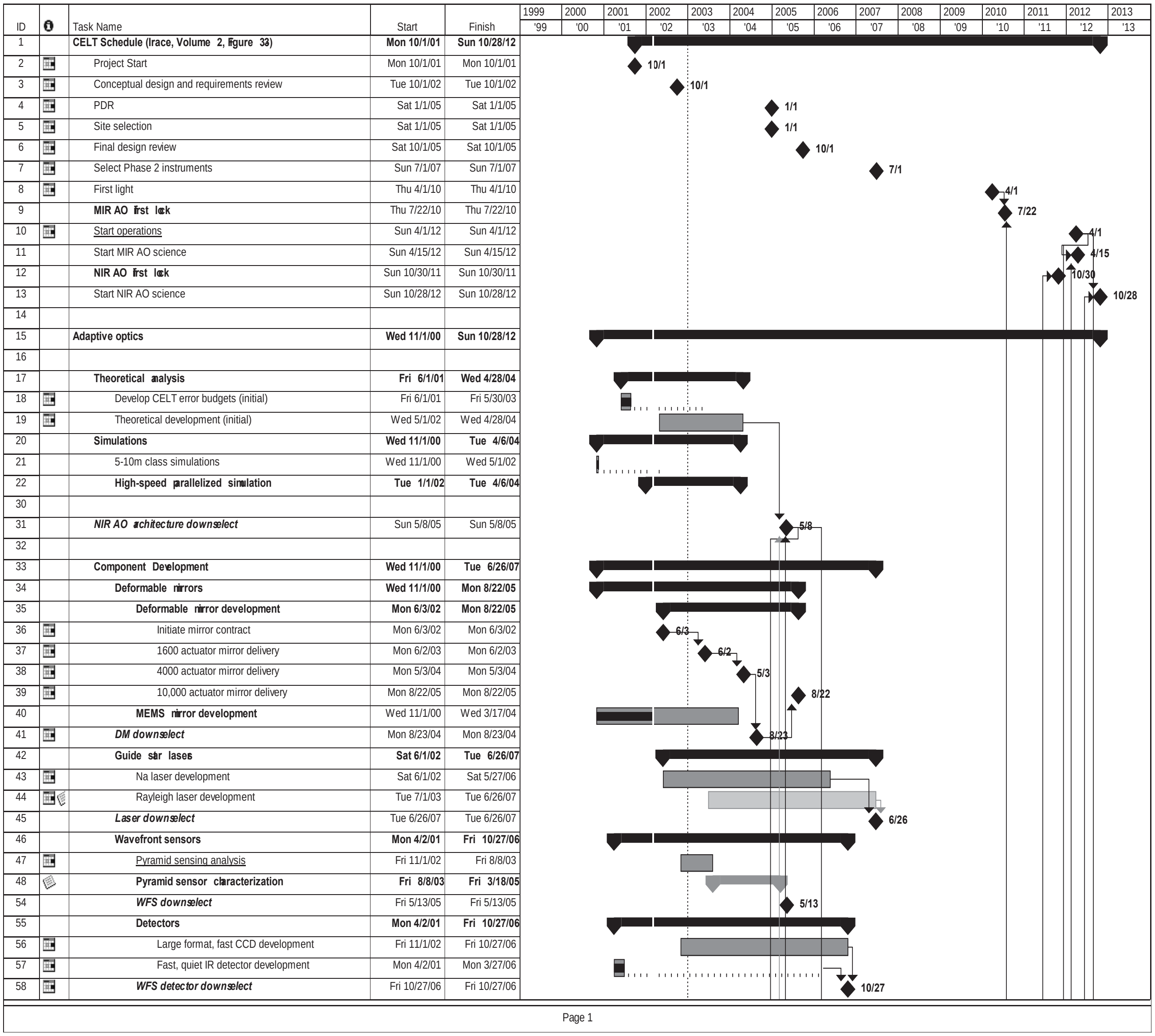
The demonstration of key AO architectural elements will do the following

1. Reduce the scope risk of CELT science and the cost risk of the CELT AO systems.
2. Validate the theoretical and numerical simulation analysis upon which the AO system architecture will be based.
3. Validate key component performance in real-world conditions.
4. Guide software functional requirements for CELT AO through scientific use of the field demonstration systems.
5. Train a generation of AO engineers who will carry forward their expertise to CELT system design, integration and test, and operations.

Palomar Multi-conjugate Adaptive Optics (PALMAO) Testbed
The existing AO system at Palomar Observatory provides an ideal testbed for the development of the key CELT AO technologies. The 5.1 meter diameter telescope on Palomar Mountain is sufficiently large to investigate the limitations imposed by focal anisoplanatism on individual Na LGS, and the precision of tomographic reconstruction using multiple guide star wavefront sensing.

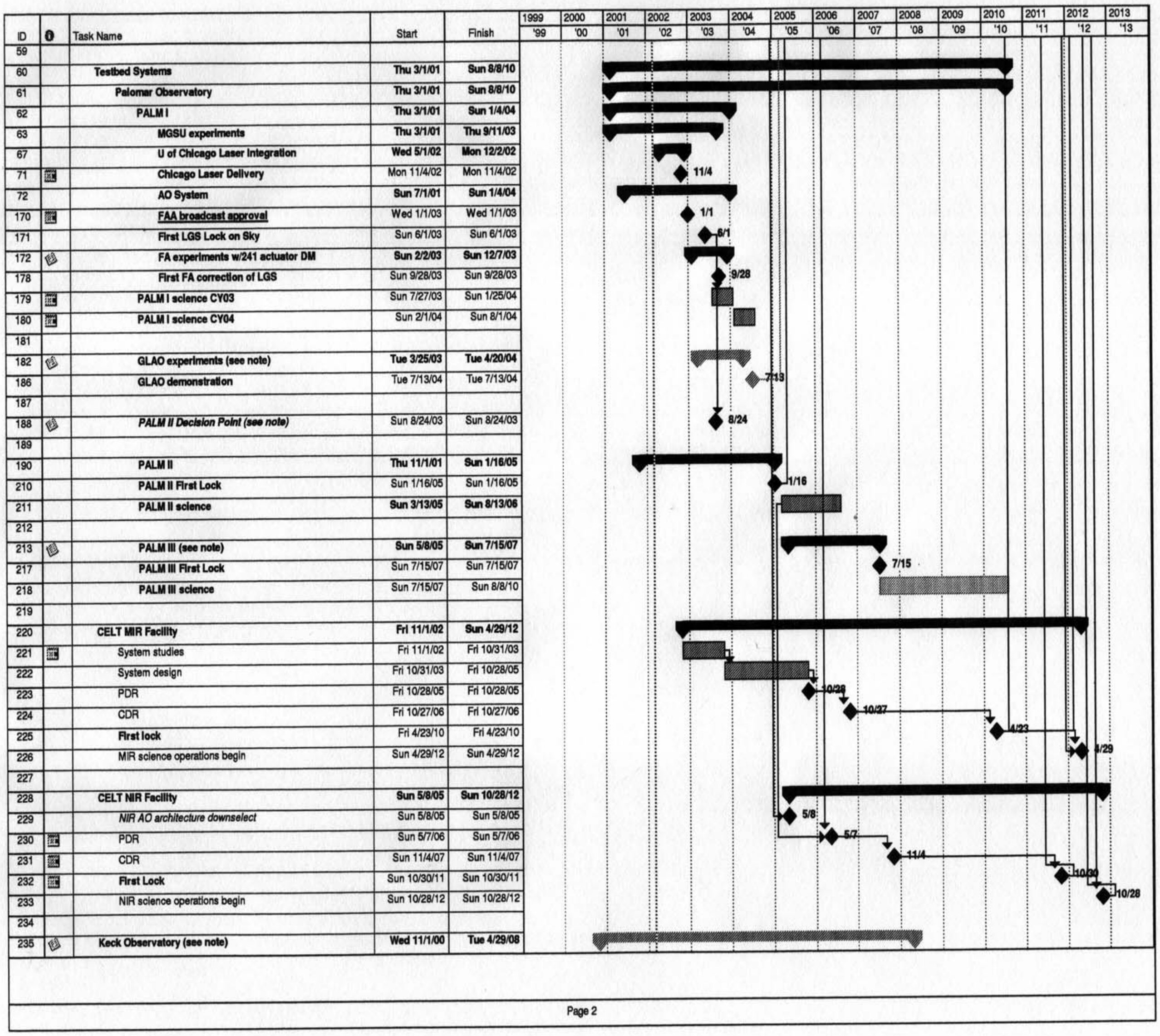
Development of a four-channel Shack-Hartmann wavefront sensor for the PALMAO system is already underway. During summer 2002, the existing AO system will be reconfigured to conduct tomographic experiments. The design of the PALMAO program enables demonstration of the key CELT AO issues prior to the downselection of the CELT NIR AO architecture and prior to the Final Design Review for the observatory construction program. (For details, see R. Dekany, "The Palomar Multi-conjugate Adaptive Optics Testbed, Revised 9/26/01.")

Keck Adaptive Optics System
The effects of segmented mirror vibration on the Keck AO system will be studied during CELT Phase 2. This will provide valuable validation of the model predictions for CELT and is likely to improve the ongoing scientific return from the Keck Observatory.



ID	ℹ	Task Name	Start	Finish
1		**CELT Schedule (Irace, Volume 2, Figure 33)**	**Mon 10/1/01**	**Sun 10/28/12**
2	▦	Project Start	Mon 10/1/01	Mon 10/1/01
3	▦	Conceptual design and requirements review	Tue 10/1/02	Tue 10/1/02
4	▦	PDR	Sat 1/1/05	Sat 1/1/05
5	▦	Site selection	Sat 1/1/05	Sat 1/1/05
6	▦	Final design review	Sat 10/1/05	Sat 10/1/05
7	▦	Select Phase 2 instruments	Sun 7/1/07	Sun 7/1/07
8	▦	First light	Thu 4/1/10	Thu 4/1/10
9		**MIR AO first lock**	Thu 7/22/10	Thu 7/22/10
10	▦	Start operations	Sun 4/1/12	Sun 4/1/12
11		Start MIR AO science	Sun 4/15/12	Sun 4/15/12
12		**NIR AO first lock**	Sun 10/30/11	Sun 10/30/11
13		Start NIR AO science	Sun 10/28/12	Sun 10/28/12
14				
15		**Adaptive optics**	**Wed 11/1/00**	**Sun 10/28/12**
16				
17		**Theoretical analysis**	**Fri 6/1/01**	**Wed 4/28/04**
18	▦	Develop CELT error budgets (initial)	Fri 6/1/01	Fri 5/30/03
19	▦	Theoretical development (initial)	Wed 5/1/02	Wed 4/28/04
20		**Simulations**	**Wed 11/1/00**	**Tue 4/6/04**
21		5-10m class simulations	Wed 11/1/00	Wed 5/1/02
22		**High-speed parallelized simulation**	**Tue 1/1/02**	**Tue 4/6/04**
30				
31		***NIR AO architecture downselect***	Sun 5/8/05	Sun 5/8/05
32				
33		**Component Development**	**Wed 11/1/00**	**Tue 6/26/07**
34		**Deformable mirrors**	**Wed 11/1/00**	**Mon 8/22/05**
35		**Deformable mirror development**	**Mon 6/3/02**	**Mon 8/22/05**
36	▦	Initiate mirror contract	Mon 6/3/02	Mon 6/3/02
37	▦	1600 actuator mirror delivery	Mon 6/2/03	Mon 6/2/03
38	▦	4000 actuator mirror delivery	Mon 5/3/04	Mon 5/3/04
39	▦	10,000 actuator mirror delivery	Mon 8/22/05	Mon 8/22/05
40		**MEMS mirror development**	Wed 11/1/00	Wed 3/17/04
41	▦	***DM downselect***	Mon 8/23/04	Mon 8/23/04
42		**Guide star lasers**	**Sat 6/1/02**	**Tue 6/26/07**
43	▦	Na laser development	Sat 6/1/02	Sat 5/27/06
44	▦ 🗒	Rayleigh laser development	Tue 7/1/03	Tue 6/26/07
45		***Laser downselect***	Tue 6/26/07	Tue 6/26/07
46		**Wavefront sensors**	**Mon 4/2/01**	**Fri 10/27/06**
47	▦	Pyramid sensing analysis	Fri 11/1/02	Fri 8/8/03
48	🗒	**Pyramid sensor characterization**	**Fri 8/8/03**	**Fri 3/18/05**
54		***WFS downselect***	Fri 5/13/05	Fri 5/13/05
55		**Detectors**	**Mon 4/2/01**	**Fri 10/27/06**
56	▦	Large format, fast CCD development	Fri 11/1/02	Fri 10/27/06
57	▦	Fast, quiet IR detector development	Mon 4/2/01	Mon 3/27/06
58	▦	***WFS detector downselect***	Fri 10/27/06	Fri 10/27/06

Figure A1-1a. Adaptive Optics development plan, page 1.



ID	🛈	Task Name	Start	Finish
59				
60		**Testbed Systems**	**Thu 3/1/01**	**Sun 8/8/10**
61		**Palomar Observatory**	**Thu 3/1/01**	**Sun 8/8/10**
62		**PALM I**	**Thu 3/1/01**	**Sun 1/4/04**
63		**MGSU experiments**	**Thu 3/1/01**	**Thu 9/11/03**
67		**U of Chicago Laser Integration**	**Wed 5/1/02**	**Mon 12/2/02**
71	▦	**Chicago Laser Delivery**	Mon 11/4/02	Mon 11/4/02
72		**AO System**	**Sun 7/1/01**	**Sun 1/4/04**
170	▦	**FAA broadcast approval**	Wed 1/1/03	Wed 1/1/03
171		**First LGS Lock on Sky**	Sun 6/1/03	Sun 6/1/03
172	✎	**FA experiments w/241 actuator DM**	**Sun 2/2/03**	**Sun 12/7/03**
178		**First FA correction of LGS**	Sun 9/28/03	Sun 9/28/03
179	▦	**PALM I science CY03**	Sun 7/27/03	Sun 1/25/04
180	▦	**PALM I science CY04**	Sun 2/1/04	Sun 8/1/04
181				
182	✎	**GLAO experiments (see note)**	**Tue 3/25/03**	**Tue 4/20/04**
186		**GLAO demonstration**	Tue 7/13/04	Tue 7/13/04
187				
188	✎	***PALM II Decision Point (see note)***	Sun 8/24/03	Sun 8/24/03
189				
190		**PALM II**	**Thu 11/1/01**	**Sun 1/16/05**
210		**PALM II First Lock**	Sun 1/16/05	Sun 1/16/05
211		**PALM II science**	**Sun 3/13/05**	**Sun 8/13/06**
212				
213	✎	**PALM III (see note)**	**Sun 5/8/05**	**Sun 7/15/07**
217		**PALM III First Lock**	Sun 7/15/07	Sun 7/15/07
218		**PALM III science**	Sun 7/15/07	Sun 8/8/10
219				
220		**CELT MIR Facility**	**Fri 11/1/02**	**Sun 4/29/12**
221	▦	System studies	Fri 11/1/02	Fri 10/31/03
222		System design	Fri 10/31/03	Fri 10/28/05
223		PDR	Fri 10/28/05	Fri 10/28/05
224		CDR	Fri 10/27/06	Fri 10/27/06
225		**First lock**	Fri 4/23/10	Fri 4/23/10
226		MIR science operations begin	Sun 4/29/12	Sun 4/29/12
227				
228		**CELT NIR Facility**	**Sun 5/8/05**	**Sun 10/28/12**
229		*NIR AO architecture downselect*	Sun 5/8/05	Sun 5/8/05
230	▦	PDR	Sun 5/7/06	Sun 5/7/06
231	▦	CDR	Sun 11/4/07	Sun 11/4/07
232	▦	**First Lock**	Sun 10/30/11	Sun 10/30/11
233		NIR science operations begin	Sun 10/28/12	Sun 10/28/12
234				
235	✎	**Keck Observatory (see note)**	**Wed 11/1/00**	**Tue 4/29/08**

Figure A1-1b. Adaptive Optics development plan, page 2.

Development Schedule

A detailed schedule of the proposed development plan, including major milestones for the architectural development and field demonstrations during Phase 2 has been developed and is shown in Figure A1-1.

A1.4 Ongoing Adaptive Optics Development

Despite the tremendous scientific advantage of extending adaptive optics from the currently targeted mid- and near-infrared wavelengths down to the visible spectrum, it is currently economically unfeasible to develop such a system. Continuing technology advancements, however, are expected to make additional adaptive optics capabilities cost effective. The CELT telescope is being designed to not preclude the deployment of an advanced adaptive optics system that could ultimately produce >50% Strehl ratio at 0.5 microns wavelength (Volume 1, Section 3.4.3)

The CELT Science Advisory Committee (SAC) will provide scientific direction to the adaptive optics team (to be located at CELT HQ), which is expected to conduct ongoing research and development in advanced AO capabilities. The CELT operations plan will contain a substantial sum for ongoing development funding for AO.

During the operations phase of CELT, it is expected that major AO upgrade projects will be undertaken under the direction of CELT HQ. The frequency of major AO upgrades during the operations phase is expected to be less frequent than the deployment of new instruments, with one major AO capability expansion expected on a decadal basis.

Appendix 2. Details of the Instrument Development Plan

This section expands on the plan to provide science instruments to the observatory that was presented in Section 4. Instrument development includes all aspects of planning, technology development, design, construction, and testing of the scientific instruments that will become part of the CELT observatory during operations. The emphasis is on instrument development in Phase 2, in particular calling out development work on those technologies that will be common to all of the CELT instruments.

A2.1 General Strategies

The CELT Phase 1 study not only generated a list of viable instrument strategies to enable much of the science case (Volume 1, Chapter 10), it also highlighted technologies and observational techniques that require further research, development, evaluation, and testing, in order to define a secure route to optimizing instrument performance and controlling cost. The general philosophy was to identify instrumentation capabilities that are achievable with currently available materials and technologies, rather than to plan for a development strategy that relied on unproven or immature techniques. Because of the very large telescope aperture of CELT and the demands of its adaptive optics program, CELT instrumentation will inevitably stretch current techniques beyond the limits with which we are familiar today. Image slicer and integral-field technologies will need to be refined; cryogenic actuation made more reliable; grating mosaics will be commonplace; large optical fabrication and support will be required; and fiber optics techniques must be brought to a higher level of maturity, reliability and performance. It is in the nature of our discipline that every CELT instrument will be required to perform at efficiencies as close as practical to its theoretical limits. This places a demand on the instrumentation program to bring those relevant technologies to proven maturity as soon as is practical.

Competing in urgency with this R&D program is the need to accelerate the instrument design process for the chosen first-light instrument suite. Some of the larger Keck (and VLT) instruments have taken 6-10 years for design, fabrication, and commissioning phases. CELT instruments will be larger and likely more complex than those we have built to date for Keck. Steps (some described in the following sections) will have to be taken to accelerate the design and construction processes for CELT instruments. It is also important to begin the process of instrument selection and conceptual design as soon as possible in order to have instruments ready for CELT start of operations.

Thus we have competing pressures for selection, design, and R&D, all of which interact in complex ways. Several questions arise. How can we make a valid selection without knowing the results of the R&D process? How can we design an appropriate R&D strategy without clear instrumentation prioritization? How can we begin the conceptual design process with incomplete knowledge of technological performance? It is for these reasons that we have chosen a balanced but conservative route to CELT instrumentation development.

The CELT Instrument Working Group (CIWG) has met regularly throughout the Phase 1 study, and has interacted with the CELT Science Working Group and Adaptive Optics Group to define a first-pass list of capabilities and instrument solutions, given in Volume 1, Chapter 10. This process produced a shopping list that was larger than our anticipated budget, and hence there is further work to do in culling that list to define an acceptable first-light instrument suite. This culling and refining process is explicitly scheduled in the instrument development plan and is anticipated to involve members of all of the CELT working groups. However, science requirements, tempered with sound technological advice, should be the dominant driver of this process. A by-product of this first-light instrument definition process will be both defining critical technologies for R&D focus and initiating conceptual design programs for the chosen instruments. Inherent in this plan is the recognition that the R&D and conceptual design programs will need to constantly interact and be allowed to influence and refine the instrumentation selection process.

The outcome of this culling and selection process will be a refined R&D program run in parallel with a consistent conceptual design process that will be actively monitored by the CDP. The end result of the Phase 2 instrumentation activities will be a clearer vision of technological limits; mitigation of a variety of related risks; completion (or advancement) of selected first-light conceptual designs; and the definition of further activities. This will lead to an ongoing instrumentation program that will target required instrument capabilities for second generation and beyond.

A2.2 Administrative Approach

Many of the scientific instruments envisaged to achieve the CELT science goals are beyond the scope of any particular university research lab. This is due in part to their size and complexity. It will be essential to establish a consortium of contributing institutions and to subcontract to industry. Experience shows, however, that astronomers committed to carrying out science with the proposed instruments are needed at the helm in order to develop the correct and necessary Level 1 requirements, guide the conceptual design, and participate fully in the final system integration and testing. Similarly, a significant fraction of the R&D needed to advance state-of-the-art customized astronomical instrumentation is best carried out in well-founded university labs within the CELT community, and through partnerships with other organizations. Support for labs within the CIT/UC community will be important. To obtain the best possible implementation of the selected CELT instruments, we will build on lessons learned at the Keck Observatory and adopt higher standards of project management, project engineering, and scientific oversight than in previous undertakings of this kind. We will place significant emphasis on the pre-Phase 3 design studies in order to ensure that projects are well understood and feasible from the outset.

The following administrative approach will be adopted for each selected instrument:

- Each instrument must have a dedicated, full-time scientific Principal Investigator of sufficient standing to provide effective leadership. A science team should support the PI. This team will be expected to play a significant role in the integration and testing phases.
- Each instrument team must identify a Project Manager and a Project Engineer who will work closely with the CDP-appointed Instrumentation Manager, to ensure that proper project management discipline is being followed at all times, and that standardized reporting methods are in place.
- No project will be undertaken without a significant and satisfactory pre-Phase 3 design study, including a detailed budget, schedule and management plan.
- All instrument projects will be subject to external review (see Section 4.3.5).
- Initially, funding will only be awarded to preliminary design review.
- Whenever possible, commercial off-the-shelf products should be used. The instrument teams should appeal to industry for fixed-price contracts for fabrication and procurement whenever possible.
- R&D activities will be required in numerous areas. In some cases this activity must occur in industry and will require development funding. In other cases, the research will be best carried out

in specialized university or government labs. In either case, the project must be well defined or the problem well-posed in order to receive funding through the CDP. Standardized reporting disciplines should be employed.

- R&D tasks will generally be assigned to the selected instrument developers. Sharing synergistic tasks among selected developers will be encouraged. R&D tasks that are not managed by instrument developers will be discouraged.
- Each instrument will be delivered with a data reduction pipeline.

Instrument projects will be subject to review and audit through the mechanisms set up by the CDP.

A2.3 Risk Mitigation

We identify here, in broad outline, four risk categories for instrumentation development and our approach to mitigating those risks.

- **Technology risk:** Mitigation will be achieved through an active R&D program, initially matched to the first-light instrumentation suite, that will evolve through an interactive process with design and agreed-upon science imperatives.
- **System risk:** This covers issues related to detailed system analyses of the combined effects of atmosphere, telescope, adaptive optics, instrument performance, data reduction, and science analysis. Mitigation will be achieved through full-system modeling of all components in the chain to support instrument design decisions
- **Time/cost risk:** The worldwide astronomical community has an extensive history of instrumentation projects that have suffered from slipped time-lines and cost overruns. The development of instruments for large telescopes in the 8-10 meter class have often suffered from a “small instrument” culture attempting to take on projects in the multi-million dollar régime. The Keck experience has taught us valuable lessons, advancing the view that much stricter project management and control protocols must be in place from the initiation of the project.
- **Scope risk:** Inevitably, science requirements evolve with time, and over the course of a long developmental program different priorities emerge. The first-light instrument program, however, has to be defined and settled upon in an early phase of work in order to ensure effective use of the telescope from its deployment.

A2.4 Schedule and Budget

As encapsulated in the Gantt chart below (Figure A2-1), a strawman plan has been developed which schedules and attempts to place costs on the relevant R&D activities (items 4-18), as discussed in Volume 1, Section 10.7. It simultaneously schedules concept designs on a number of the front-ranked instruments (e.g., items 20, 28 and 36). The plan is phased in such a manner that particular designs follow the relevant R&D activities in a natural progression. Also explicitly shown in the plan are the instrument priority studies (item 2) that will set the stage for transforming this strawman plan into a real body of work. Clearly, since that pivotal set of meetings (spanning a period of ~3 months) is in the future, we are somewhat constrained in solidifying our R&D and design plans at this stage.

We have confidence that the set of instruments and capabilities already been defined in Volume 1, Chapter 10 closely matches the CELT science requirements for both AO and seeing-limited foci. Hence, these conclusions are used as a base for current budgetary and resource estimates. For example, it should be noted that while the majority of Chapter 10 instruments are featured in the Gantt chart, the R&D activities are principally targeted at the development of first-light seeing instrument capabilities (namely MTHR), its fiber positioner (CfP), and what is arguably the highest priority MCAO-fed instrument (the d-IFU). It is entirely possible that such priorities will change in the initial priority studies, and even within the R&D phase itself; however, the scope of the undertaking (i.e., a substantial R&D effort combined with phased concept design work) is unlikely to change dramatically in its overall scope of work.

The scope and cost of each R&D activity have been based on the assumption that a large fraction of the work will be done in the UC/Caltech environment. Explicitly factored in is a mix of disciplines (project management; instrument scientist; mechanical, electronic and software engineering; trades), supplemented where necessary with contract work (e.g., optical design, IFU fabrication, etc). If, in addition, we assume that the majority of the concept design work is also in-house, the project plan (assuming the full R&D plan with three separate concept design packages) requires a team of ~9 FTEs in steady state through the three-year Phase 2 activities. On this conservative assumption, a three-year budget total of ~\$11M - \$13M is required to support these activities. Given the scope of the concept design activities, we may wish to contract outside industry for much of this non-R&D work. While this is unlikely to reduce our funding requirements for Phase 2, it may be seen as a more efficient use of our resources, especially if (as seems likely) we follow by externally contracting the detailed design and fabrication phases. Such complex issues have yet to be decided and are inevitably part of a complex, interdependent set of decisions that may have to be made on a case-by-case basis.

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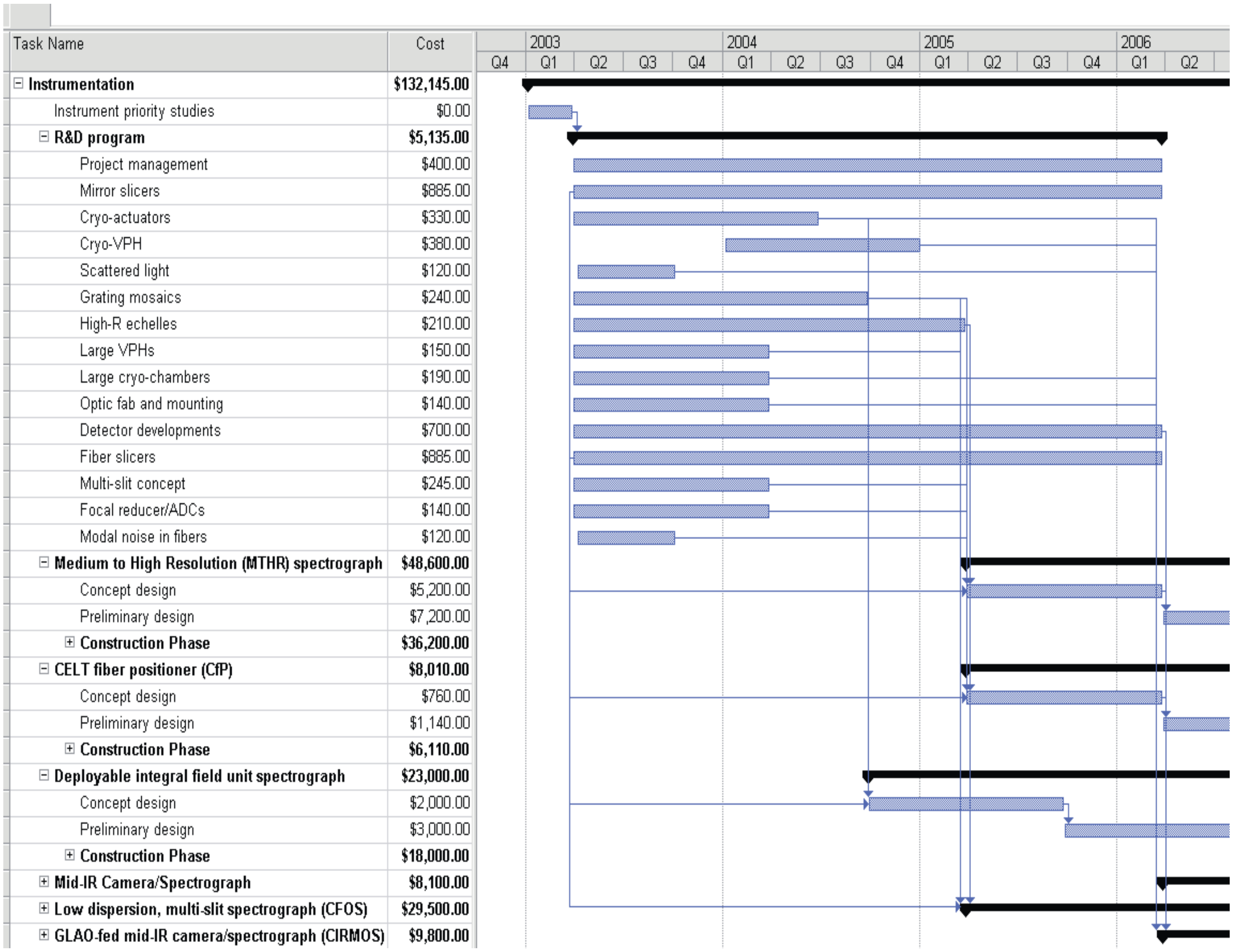

Task Name	Cost
⊟ **Instrumentation**	**$132,145.00**
Instrument priority studies	$0.00
⊟ **R&D program**	**$5,135.00**
Project management	$400.00
Mirror slicers	$885.00
Cryo-actuators	$330.00
Cryo-VPH	$380.00
Scattered light	$120.00
Grating mosaics	$240.00
High-R echelles	$210.00
Large VPHs	$150.00
Large cryo-chambers	$190.00
Optic fab and mounting	$140.00
Detector developments	$700.00
Fiber slicers	$885.00
Multi-slit concept	$245.00
Focal reducer/ADCs	$140.00
Modal noise in fibers	$120.00
⊟ **Medium to High Resolution (MTHR) spectrograph**	**$48,600.00**
Concept design	$5,200.00
Preliminary design	$7,200.00
⊞ **Construction Phase**	**$36,200.00**
⊟ **CELT fiber positioner (CfP)**	**$8,010.00**
Concept design	$760.00
Preliminary design	$1,140.00
⊞ **Construction Phase**	**$6,110.00**
⊟ **Deployable integral field unit spectrograph**	**$23,000.00**
Concept design	$2,000.00
Preliminary design	$3,000.00
⊞ **Construction Phase**	**$18,000.00**
⊞ **Mid-IR Camera/Spectrograph**	**$8,100.00**
⊞ **Low dispersion, multi-slit spectrograph (CFOS)**	**$29,500.00**
⊞ **GLAO-fed mid-IR camera/spectrograph (CIRMOS)**	**$9,800.00**

Figure A2.1. Gantt Chart for Research and Development, and Concept Design Activities