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 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.

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.