Center for Adaptive Optics

Annual Report
August 1, 2005

Program Year 6
Reporting from November 1
2004 to October 31 2005

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1.1. General information on participating institutions:

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<tr>
<td>Reporting period</td>
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<td>Role of Institution at Center</td>
<td>Lead institution in Vision Science Research</td>
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<td>Role of Institution at Center</td>
<td>Eye Motion Algorithms</td>
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<td>Lawrence Livermore National Laboratory</td>
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<td>Role of Institution at Center</td>
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<td>Role of Institution at Center</td>
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1.2. Biographical Information for Each New Faculty Member by Institution.

See Appendix A.

1.3. Executive Summary

The Center for Adaptive Optics (CfAO) will complete Year 6 as a Science and Technology Center on October 31, 2005. National Science Foundation funding for the Center is projected through to Year 10 (October 31, 2009). This report describes the Center’s status as of August 1, 2005.

As an outcome of intensive strategic planning, in March 2001 the membership of the CfAO developed and endorsed a statement of its mission, goals and strategies. To address these goals, commencing in November 2002 (Year 3) the Center reorganized its research into Themes. In this report, the efforts and accomplishments of the CfAO are organized in accord with these Themes.

1.3.1. CfAO Mission, Goals and Strategies

Mission: To advance and disseminate the technology of adaptive optics in service to science, health care, industry, and education.

Goal: To lead the revolution in AO, by developing and demonstrating the technology, creating major improvements in AO systems, and catalyzing advances nationwide within the next decade.

Strategies: CfAO will pursue its purpose and achieve its goal by:
1. Demonstrating the power of AO by doing forefront science.
2. Increasing the accessibility of AO to the scientific community.
3. Developing and deploying highly capable AO systems and laser beacons.
4. Coordinating and combining research efforts to take advantage of the synergies afforded by the Center mode of operations.
5. Integrating education with our research.
6. Building a Center community that is supportive of diversity through vigorous recruiting, retention, and training activities.
7. Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology.
8. Leveraging our efforts through industry partnerships and cross-disciplinary collaborations.
1.3.2. Themes

The Theme structure continues to positively impact the Center’s Education and Research programs. Center investigators are encouraged to develop collaborative programs both within Themes and between Themes. Collaborations between vision scientists and astronomers are particularly encouraged. A description of the CFAO’s themes follows.

Theme 1: Education

This is a crucial CfAO activity, and its integration with our research is an important challenge. Specific goals and initiatives of our Education program include:

- Increasing the versatility of Center students and post-doctoral researchers.
- Establishing a center-based model for retention and advancement of college-level students from under-represented groups:
- Increasing the number of high school students from under-represented groups who are prepared to pursue a science/technology/mathematics degree in college:
- Working with Hawaiian institutions to improve the educational infrastructure and consequently the training and retention of native Hawaiians in the science and technology workforce.

The impact of CfAO EHR activities is measured by our success in each of the four interwoven strategies:

- TOOLS. Implement activities and programs that broaden access to CfAO related fields.
- PRACTICES. Involve CfAO members in CfAO EHR programs and activities, and more specifically in educational practices that broaden participation.
- PARTNERSHIPS & LINKAGES. Develop linkages and partnerships that broaden participation in the CfAO and CfAO sites.
- PEOPLE. Advance students that will broaden participation of the CfAO and CfAO fields.

The Education Theme was rated excellent by Site Visit committees in 2003 and 2004.

Theme 2: AO for Extremely Large Telescopes (ELTs)

The highest recommendation of the National Academy of Sciences’ Astronomy and Astrophysics Survey Committee (2001) was the design and construction of a ground-based 30-m telescope, equipped with adaptive optics - a giant segmented mirror telescope (GSMT). At a wavelength of 1µm, the diffraction-limited resolution of a 30-m telescope will be 0.007 arc seconds, and would provide a qualitative jump in our power to understand the cosmos. Developing the adaptive optics systems for this telescope is extremely challenging and will require developments in most technical areas of adaptive optics. Making a major contribution towards achieving this national priority is a natural and suitable objective for the CfAO.

The CfAO strategy in this Theme is to develop crucial concepts and components needed for successful implementation of AO on ELTs, recognizing that the actual implementation for a 30-m telescope will require major resources from some other
source. Consequently the CfAO is concentrating on developing fundamental understanding and analysis tools, on proof-of-principle laboratory experiments, and on key hardware prototypes. AO designs and feasibility tests that are specific to one or another of the Extremely Large Telescope designs are funding by those projects, not by the CfAO.

Effective adaptive optics on large mirror aperture (e.g. 30m) telescopes will require using multiple laser beacons to perform three dimensional tomography of atmospheric turbulence above the telescope. By sampling the turbulence in real time at different angles to the optical axis, one can solve for the three dimensional structure of the turbulence. An exciting new development at the CfAO in the past year has been the “multi-object AO” (MOAO) concept, in which a small MEMS-based AO system is placed in the focal plane above every object of interest (e.g. each distant galaxy in a field), and the output of each AO system is sent via optical fibers to a spectrograph. The individual MEMS AO systems would be reconfigured for each new galaxy field. For applications in cosmology and large-scale structure, such a system could operate within a relatively wide field (e.g. 3 arc min) without the necessity of multiple large-diameter deformable mirrors.

Multi-Object AO requires determining the tomography of the atmosphere with multiple laser guide stars (LGS), computing atmosphere corrections in set directions, and applying the computed corrections in those directions – open loop and over many individual small fields. MEMS deformable mirrors are likely to be a technology of choice.

CfAO researchers have successfully sought additional sources of funding in Theme 2, including the privately funded Laboratory for Adaptive Optics at UC Santa Cruz which is a partner in the Theme 2 effort. CfAO members continued to participate in NSF’s roadmap process for AO, which guides the NSF AO national development program (AODP) for astronomical adaptive optics, and in the Thirty Meter telescope (TMT) consortium consisting of AURA, ACURA, the University of California and the California Institute of Technology. The TMT consortium has a funding commitment of about $60 million over the next four years, with a substantial amount directed at AO design and key component development. The majority of members of the Adaptive Optics Working Group for the TMT belong to the CfAO. In addition, CfAO members are participating in the design of AO several different AO systems for TMT, under TMT funding.

**Theme 3: Extreme Adaptive Optics (ExAO), Enabling Ultra-High-Contrast Astronomical Observations**

The ExAO Theme’s goal is to achieve high-contrast imaging and spectroscopic capabilities to enable the detection and characterization of extra-solar planetary systems and their precursor disk material. By improving image quality and reducing scattered light, ExAO systems will enable the detection of faint objects (such as planets) close to bright sources (parent stars) that would otherwise overwhelm them. This is accomplished both by increasing the peak intensity of point-source images and by removing light scattered by the atmosphere and the telescope optics into the “seeing disk”. This
combination of improvements can dramatically improve the achievable contrast ratio for astronomical observations. In 2004, Gemini Observatories awarded CfAO and another institution $200,000 each to develop a design and construction plan for a high contrast coronagraphic Extreme AO system. CfAO and partners were subsequently selected to build the AO system and coronagraph, and the recommendation has been forwarded to the Gemini Board for approval. As of this writing, the Board’s approval for all new instrumentation for Gemini has been delayed because of funding and other issues that have arisen. The delay in approval has necessitated the proposed Year 7 budget for Theme 3 to be contingent upon the receipt of Gemini funding. An alternative budget has been prepared if this funding is not received. The Laboratory for Adaptive Optics at UC Santa Cruz is a partner in these design and simulation studies.

The CfAO continues to use a professional project manager for the ExAO theme. Budgets and Gannt charts are updated to clearly delineate sources of funding, schedules, and deliverables that can be achieved under varying credible funding scenarios.

**Theme 4: Compact Vision Science Instrumentation for Clinical and Scientific Use**

Scientists and engineers participating in the Vision Theme have focused their efforts on the development of ophthalmic instrumentation equipped with AO, with the ultimate goal of commercialization. This requires the development of low-cost, compact, and robust devices that can be used by clinicians who are unskilled in adaptive optics. The development of inexpensive, small, and high stroke deformable mirrors continues to be a critical factor for achieving broad dissemination of the technology. In 2004 CfAO supported four groups working on new deformable mirror technologies. Investigators continue to demonstrate new science applications for adaptive optics for understanding normal vision and retinal organization, with particular emphasis on three-dimensional imaging of the living retina. In addition they are exploring the value of adaptive optics in the diagnosis and treatment of retinal disease.

1.3.3. **Research Management**

**Conferences** - The Center organizes annual Fall Retreats aimed at attendance by all researchers, graduate students, and postdocs. This year’s Spring Retreat was focused on strategic planning for Center programs through to Year 10 and beyond. In addition, smaller workshops and symposia on specialized topics are held during the year as the need arises.

In the spring of each year, researchers forward their proposals to the CfAO for continuing or new research. Proposals are reviewed by external and internal reviewers and then discussed in committee. Those “on the edge” are directed to the Program Advisory Committee (PAC) for discussion and advice. Funding decisions are typically made by the end of June each year. The annual cycle for funding begins each November 1.

**Scientific management** is provided by the Director and the Center’s Executive Committee (EC), made up of Center representatives including Theme leaders. The EC meets biweekly utilizing video- and telephone-conferencing links. The Center Director and EC
are assisted by two external committees, the External Advisory Board (EAB) and the Program Advisory committee (PAC). The EAB meets annually and advises on strategic issues and directions that the Center needs to pursue. It reports to a University oversight committee chaired by the Vice-Chancellor for Research at UCSC. The PAC also meets annually and assists in ensuring the scientific and technical vitality of the Center’s research program, reporting to the CfAO Director. UC Santa Cruz oversight is via our Oversight Committee, consisting of the Vice Chancellor for Research, the Dean of Physical and Biological Sciences, the Dean of Engineering, the Director of Lick Observatory, and other key officials. The Oversight Committee meets annually.

**Administrative management** - The Center has a Managing Director (reporting to the Director) who is responsible for the day-to-day management and oversight of the various CfAO activities. This includes budget matters, arrangements of retreats, workshops, and summer schools, report writing, facilities, etc.

### 1.3.4. Partnerships

The objective of CfAO’s partnership activities is to enhance the Center’s ability to fulfill its research and education goals. The Center is pursuing this objective through:

- Leveraging its efforts through industry partnerships and cross-disciplinary collaborations.
- Stimulating further investment by government and industry sources in AO research and development
- Catalyzing the commercialization of AO technologies leading to technological advancements relevant to CfAO research objectives and enabling broader use of adaptive optics.

The CfAO has ongoing partnership activities with 13 optics and micro-electronics companies, 5 national laboratories, 5 non-CfAO universities, 6 astronomical observatories, and 2 international partner institutions. The Education program has in addition developed 22 partnerships both in Hawaii and on the mainland. The former include the Maui Economic Development Corporation, high tech companies in Hawaii, educational institutions, the Air Force in Maui, and several Observatories.

Key partnership activities in our research Themes are with the Thirty Meter Telescope Project (Theme 2), and with the Gemini Observatory (Theme 3).

### 1.3.5. Highlights for Year 6

**Theme 1: Education and Human Resources**

1. **Expansion of Hawaii Akamai Internship programs and short courses.** Based on the success of our Maui internships and short course, this year we expanded these activities to the Big Island of Hawaii as well, with active participation from the astronomical observatories located there.
2. **High Rate of Intern Retention.** Of the 43 interns who completed their CfAO internships between 2002 and 2004, the retention rate in science, technology,
engineering, and mathematics related activities ranges from 86-93% for our internship programs. This high retention rate is very encouraging.

3. CfAO Professional Development Workshop. This annual event brings together graduate students, postdoctoral researchers, and education partners for an intensive week of activities on teaching and learning science. In Year 6 the returning participants were given advanced leadership roles in the workshop. We developed many opportunities for workshop participants to pilot their new teaching skills, and reflect on their experience with peers. The combination of workshop and teaching experience has led to the development of many new inquiry activities and a cadre of reflective science teachers with proficiency in inquiry based teaching approaches.

Theme 2: AO for Extremely Large Telescopes
1. Leadership. CfAO researchers continue as strong leaders within the extremely large telescope astronomy community, engaging in studies for almost all aspects of the Thirty Meter Telescope (TMT) design.

2. Multi-Object Adaptive Optics. CfAO members explored several different multiple-guide-star tomographic measurement and reconstruction methods. An exciting new development is the “multi-object AO” (MOAO) concept in which small MEMS-based AO systems are placed in the focal plane above each object of interest (e.g. each distant galaxy), and the output of each AO system is sent via optical fibers to a spectrograph slit. For applications in cosmology and large-scale structure, such a system could operate within a relatively wide field (e.g. 3 arc min) without the necessity of multiple large deformable mirrors.

3. The Chicago Sum Frequency Laser (CSFL) was delivered to Mt. Palomar Observatory in May 2004. The prototype laser has achieved a power output of approx. 5 watts. Work is now proceeding to integrate the laser into the Mt. Palomar AO system.

4. Black hole at the Galactic Center. CfAO astronomers discovered a variable point source, imaged in the L' band (wavelength 3.8 µm) with the Keck II telescope's adaptive optics system, that is coincident to within 18 milli-arc sec of the Galaxy's central supermassive black hole and central radio source Sgr A*. This is the first infrared or optical imaging of the point source coincident with the position of the central black hole. We suggested that the variable 3.8 µm emission and the X-ray flares arise from the same underlying physical process, possibly the acceleration of a small population of electrons to ultrarelativistic energies. In contrast to the X-ray flares which are only detectable ~2% of the time, the variable 3.8 µm emission provides a new, constantly accessible, window into the physical conditions of the plasma in close proximity to the central black hole.

Theme 3: Extreme Adaptive Optics
1. Extreme Adaptive Optics for the Gemini Observatory. The CfAO team was successful in its design and development bid for a high contrast extreme AO coronagraph for the Gemini Observatory. Funding approval for building the instrument at a level of $20 million is currently before the Gemini Board. If approval is received the project will start this year (2005)
2. **Laboratory for Adaptive Optics.** The Laboratory for Adaptive Optics was dedicated on May 17, 2005. It is now fully operational. Laboratory studies are underway on extreme adaptive optics and on AO tomography for extremely large telescopes.

**Theme 4: Vision Science**

1. **Spectral Domain Optical Coherence Tomography.** One of the most exciting new CfAO instruments developed during Year 6 has been the spectral-domain OCT system equipped with adaptive optics, developed by Don Miller and his group at Indiana University.

2. **Eye Movements.** An unexpected outcome is that adaptive optics has now provided vision science with new instrumentation to measure eye movements that is superior in resolution to any other technique.

3. **MEMS Deformable Mirrors.** Year 6 has seen a turning point in our mirror development efforts. In April, Boston Micromachines delivered mirrors to Berkeley, Indiana University, LLNL, and Rochester with 3.5 microns of stroke. The mirrors have 140 actuators and are 4.8 mm on a side and have a comparable in performance to Xinetics mirrors, which have been the standard DM for vision science applications to date.

4. **Adaptive Optics Phoropter.** On July 22, 2005, the phoropter developed by Lawrence Livermore National Laboratory and with the Xinetics mirror replaced by the MEMS Deformable Mirror was successfully demonstrated to representatives from Bausch and Lomb at the University of Rochester. The phoropter was transferred to Bausch and Lomb for further testing.

**1.3.6. Closing remarks**

In this sixth year of the CfAO, we have seen significant advances toward our research and education goals which have continued to progress in accordance with our strategic plan. We are looking to the future, beyond year 10 (when NSF funding ends) and have scheduled a Strategic Planning Retreat commencing August 4, 2005 at Half Moon Bay, CA, to identify opportunities and develop on-going plans for the future.
2. RESEARCH

2.1. Center’s Overall Research Objectives

The overall research objectives of the Center are:
To use and promote existing Adaptive Optics (AO) technology in the service of Astronomical and Vision Science in particular, and science in general.
To improve the technology associated with Adaptive Optics (AO) components and develop improved AO systems for both Astronomy and Vision Science. These systems incorporate improved performance and robustness together with reductions in dimensions and cost.

Our broad research objectives remained unaltered in Year 6. As in earlier years, the Center’s research is organized into Themes. These Themes are AO for Extremely Large Telescopes, Extreme Adaptive Optics, and Compact Vision Science Instrumentation. The thematic approach has encouraged collaboration between researchers both within and across our Themes.

2.2. Performance and Management Indicators.

In their research proposals for Year 6, Principal Investigators (PI’s) identified the specific milestones that would be achieved for each of their projects in the coming year. During the year and particularly during the renewal cycle all progress reports are assessed on the milestones achieved and, where appropriate, the reasons underlying failure to do so. The Proposal Review Committee (PRC) reviews all renewal proposals and recommends funding levels to the Director based on performance against milestones.

2.3. Problems

Current issues that the CfAO is working on are:

1. Vision Science researchers continue to seek ways to accelerate the availability of commercial instruments based on the technologies being developed by the CfAO.

2. As mentioned in last year’s report, while commercially available MEMS deformable mirrors have improved markedly in performance each year, they still do not meet a prime requirement of vision scientists and for certain AO applications in astronomy, namely 10 micron stroke. High stroke MEMS deformable mirrors are considered a critical AO component for the future Thirty Meter Telescope. Theme 2 is providing additional funds for MEMS deformable mirror development. These high stroke mirrors will have applicability in vision science as well as astronomy.
2.4. Research Thrust Areas

2.4.1. Theme 2: Adaptive Optics for Extremely Large Telescopes

The highest recommendation of the National Academy of Sciences’ Astronomy and Astrophysics Survey Report for ground-based astronomy\(^1\) was the design and construction of a 30-m telescope equipped with adaptive optics. Developing an adaptive optics system for such a telescope is extremely challenging and requires an extension of almost every aspect of AO system design and component technology. The CfAO objective in this Theme for the second five years of the Center is to make a major contribution towards achieving this national priority, especially in areas where cross-institutional and multidisciplinary collaboration is required.

In Year 6 Theme 2 of CfAO was operating on a plan that stressed four specific development areas: 1) Develop at least one workable “point design” for multi-conjugate adaptive optics on a 30-m telescope; 2) Develop partnerships to co-fund long-range hardware technology development for key AO components, including laser guide stars; 3) Develop techniques for doing quantitative astronomy with laser guide stars; 4) Pursue astronomical science related to AO on 30-m telescopes, especially using laser guide stars, deconvolution methods, and spatially resolved spectroscopy. These goals represented areas where the CfAO and its “center mode of operation” make a unique contribution to astronomy. The top level of the roadmap is shown in Figure 2.4.1.1.

For Year 7 and beyond, we have modified the emphasis of this Theme, which will now focus on three main areas: 1) MEMS deformable mirror development, 2) Astronomical science observing using AO and laser guide stars, and 3) (to a lesser degree) Sodium guide star laser development. The readjustment reflects several developments during Year 6: A) The main theoretical results and concepts for a workable “point design” for an MCAO system (and new variants, such as MOAO) have been largely completed. A

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number of large telescope projects have now received funding for design studies and are picking up a the more detailed AO design efforts. Many of the participants in the CfAO-funded analysis and modeling activity are now key players in these telescope design efforts. B) It has been recognized that in order for the CfAO to have an impact on AO component development, a goal for completion by Year 10 (the “sunset” year for our NSF STC funding) should be to successfully demonstrate two key components: a MEMS deformable mirror and a pulsed guide star laser. Accordingly, in Year 7 we will be directing our component development funding more strongly towards those approaches that, to date, have shown the most progress and promise with CfAO funding. In a sense, this is a technology down-select with the goal being to complete demonstrations of feasible technologies rather than to provide seed funding for a wide variety of new approaches.

This report reflects the progress of projects funded under the earlier plans formulated for Year 6.

### 2.4.1.1. Feasible point design for an ELT AO system: Analysis and Modeling

Extremely Large Telescopes (diameter 20 – 30 meters) will require multi-laser guide star tomographic wavefront reconstruction, in which multiple laser guide stars (or natural stars if available) are used as reference beacons (Figure 2.4.1.2). With multiple beacons, tomographic reconstruction of the atmosphere is possible: one can solve for the entire 3D structure of atmospheric turbulence above the telescope\(^2\).\(^3\). Multiple lasers are also essential when using laser guide stars with a 30-m telescope in order to overcome the “cone effect”: the failure of a single laser guide star at a finite altitude to fully probe the cylindrical volume of air above the telescope. The cone effect is more severe for larger telescopes.

During Year 6, CfAO members explored several different multiple-guide-star tomographic measurement and reconstruction methods. An exciting new development is

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the “multi-object AO” (MOAO) concept in which small MEMS-based AO systems are placed in the focal plane at the location of each object of interest (e.g. each distant galaxy), and the output of each AO system is sent via optical fibers to a spectrograph slit. For applications in cosmology and large-scale structure, such a system could operate within a relatively wide field (e.g. 3 arc min) without the necessity of multiple large-diameter deformable mirrors.

For applications requiring an entire field of view to be corrected by AO (rather than multiple discrete sub-regions as in MOAO), the CfAO has continued to explore multi-conjugate AO (MCAO) methods in which multiple large-format deformable mirrors are used in series, with each mirror optically conjugate to a different height in the atmosphere. Quantitative analysis of MOAO and MCAO concepts is required to evaluate their performance and to make practical decisions about the number of laser beacons, laser beacon power, number of conjugate deformable mirrors, and degrees of freedom required. Progress in Year 6 has led to a set of analytical scaling models that parameterize key design issues of the MCAO and MOAO concepts. In addition, we have implemented both more efficient and more accurate versions of AO simulation codes which can now more rapidly explore parameter space for design insight.

In Year 3 the CfAO initiated a long-term collaborative project in analysis, modeling, and simulation for AO on extremely large telescopes (ELT’s) that continued into Year 6. This project involves 12 CfAO researchers from 5 member institutions, including members implementing AO systems on telescopes at Lick, Keck, Palomar, and Gemini Observatories, as well as researchers from Lockheed. After prioritization of outstanding ELT AO design issues, four key "show-stopper" issues were identified:

• Quantify the cone-effect when using multiple laser guide stars
• Mitigate laser guide star spot elongation
• Develop an optical design that gets the laser guide star light through the AO relay optics without severe aberration
• Optimize AO reconstruction and tomography algorithms for MOAO and MCAO

Specific modeling tools developed include:

• Analytic scaling laws that relate the number and placement of guide stars (natural and laser), deformable mirrors, and wavefront sensors to tomographic reconstruction accuracy over a wide field of view
• Semi-analytic computer models that compute statistically averaged AO performance as a function of design parameters
• Massively parallel Monte-Carlo simulation codes that implement AO models in detail and execute rapidly enough to perform practical design trade-off studies
• Documented validation procedures for the AO models at each level.

Models are being tested using both laboratory and observatory data. As CfAO tools are developed, they are distributed first to the CfAO community for testing and validation, and then to the broad astronomy community. The AO for ELT Analysis Modeling and Simulation project has a set of web pages on the CfAO web site: http://cfao.ucolick.org/research/aoforelt/
The Table below summarizes the CfAO’s computer simulation and modeling code efforts to date. Arroyo (a C++ object library with high fidelity atmosphere, telescope, and AO component modeling), CIBOLA (Covariance Incorporating Basic Option for Linear Analysis, a second order covariance analysis and AO PSF modeling code written in Matlab⁴), and PAOLA (Performance of Adaptive Optics for Large Apertures, a set of functions and procedures written in IDL for calculating the performance of an AO system) are available on the CfAO’s software distribution web site, http://cfao.ucolick.org/software/index.php

<table>
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<tr>
<th>Name</th>
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<tr>
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<tr>
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<td>Analytical Scaling laws</td>
<td>UNIX, Parallel supercomputer (ported to MHPCC)</td>
<td></td>
</tr>
<tr>
<td>Arroyo</td>
<td>(Object Oriented class library for AO optical elements)</td>
<td>Spatial</td>
<td>Diffractive</td>
<td>Monte-Carlo Simulation</td>
<td>Accuracy</td>
<td>Validation suite of test codes against analytical models</td>
<td>UNIX, ported to LLNL supercomputer</td>
<td>Tomography algorithm implementation (nearly complete)</td>
</tr>
</tbody>
</table>

Notes: * ARCADIA (Associated Reconstructor Computations, Analytically Derived and Including Anisoplanatism) generates sparse MCAO reconstructors offline

2.4.1.1. Specific analysis and modeling results

MCAO/MOAO scaling laws: These performance scaling laws are now well established for the 30 meter telescope case. Extension of the technique to spherical waves (see Figure 2.4.1.3) has allowed us to predict the “cone effect” caused by the sodium guide stars being at finite altitude. Tomographic measurement error is driven by the density of (or mean distance between) guidestars on the field of view and by the turbulence profile. A given turbulence profile has a characteristic “layer thickness” from which a simple expression relates the tomographic measurement error to the number of guidestars.

Spot elongation: For telescopes with primary mirrors 10 meters or greater, the laser guide star spot in the sodium layer appears elongated. Several methods of mitigating spot elongation have been enumerated and studied. The most promising technique appears to be that of tracking a pulsed laser beam as it traverses the sodium layer using charge-shifting on a specialized-geometry CCD. James Beletic and Jerry Nelson are fabricating a prototype CCD device under NSF’s Adaptive Optics Development Program. Brent Ellerbroek has studied optimal centroiding algorithms for CW lasers via closed-loop simulations of 30-meter telescope MCAO systems. Options for pulse tracking via “dynamic refocus” are also under investigation. Dynamic refocus has the advantage of enabling spatial filtering at the input to the wavefront sensor, which considerably improves the sensor’s performance by reducing aliasing error.

Figure 2.4.1.3a. - Representative geometry for multi-guide star wavefront sensing. Guide star rays and science object rays travel different paths through the atmosphere. The measured wavefront is the integral of the index of refraction variations, n(x,y,z), along the path.

Figure 2.4.1.3b. - Finite-height laser guide stars produce conical bundles of rays, complicating the wavefront reconstruction process for starlight, which traverses the atmosphere along parallel rays.

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AO relay optics: Aberration of the laser beam through traditional MCAO relay optics is high, because the 90 km focus of the laser guide star spot is almost in the near field of the telescope, and varies with telescope zenith angle. A large and variable non-common path error offset would be needed in the wavefront sensor to compensate for it. Standard Hartmann sensors are unable to handle the high dynamic range of aberrations with sufficient linearity. One proposed approach is to use precision variable “zoom” optics in each wavefront sensor to partially mitigate the aberration. An alternative concept, pursued by Brian Bauman at LLNL, is to design MEMS deformable mirrors into each wavefront sensor to do the variable aberration correction. These be programmed to precisely follow the known AO relay aberrations, and they could also be run in “closed loop” to make the sensor null-seeking. Since MEMS have predictable and non-hysteretic displacement/voltage response, the tomographic wavefront measurement can be read from the deformable mirror command signal.

An alternative AO concept developed within this project is Multi-Object Adaptive Optics (MOAO) in which the laser guide star wavefront is sensed before going through the AO relay thus avoiding the AO relay optics’ aberrations. In this concept, the multiple laser guidestar measurements are processed in a tomographic reconstructor to derive commands to multiple single-deformable mirror AO systems, each system dedicated to a narrow field science object. This is a natural fit to a multi-object spectrograph instrument where a wide field is divided into multiple science channels. Linear wavefront sensors with high dynamic range (full range of atmospheric aberrations) are needed for this concept to work. Brian Bauman pursued the use of MEMS in each wavefront sensor to extend sensor linearity as described above. Lisa Poyneer investigated the use correlation signal processing to help extend the dynamic range of Hartmann sensor measurements. Much of the CfAO’s work in this area has been spurred by the science requirements of the Thirty Meter Telescope (TMT), where several different specialized AO systems will be used to feed particular science instruments.

Fast Minimum Variance Reconstructors: The “inverse” tomography problem, that is, determining the atmospheric aberrations given measurements from several guide star probes at different field angles, was approached from several perspectives in Year 6. Vogel (U. Montana, Bozeman), Gilles (Michigan Technical University and TMT), and Ellerbroek (TMT) developed sparse matrix iterative approaches which incorporate conjugate gradient search algorithms. They incorporated both multi-grid and Fourier domain preconditioners within the search algorithms to greatly reduce the number of iterations required. These techniques look feasible to implement in real time with a cluster of “state of the art” real-time processors. The techniques have demonstrated robust stability and convergence properties for closed loop (MCAO) as well as open loop (MOAO) configurations, although they are not optimal given the whole time history of measurements. Gavel (UCSC) showed theoretically that all AO reconstructors using a second order norm criterion (e.g. minimum variance or least squares) are variations of

“back-projection” tomography, where data from wavefront sensors are back projected (in the computer) along lines toward their respective guide stars in order to form volumetric estimates of the turbulence. An iterative algorithm was developed that resembles that used in computer aided tomography. The insights provided by this research have led us to propose a massively-parallel computer architecture for its real-time implementation. The proposed architecture uses hundreds of low-cost gate array chips to implement forward and backward projections through a computer estimate of the atmosphere that is distributed amongst the chips. A group of undergraduate engineering students at UCSC developed prototype gate-array chips as their capstone senior-year project.

**Optimal Wavefront Controllers:** The optimum-Strehl controller for the case of Kolmogorov turbulence with frozen flow has been derived and validated with simulations. The closed-loop minimum variance Strehl controller is an extension of minimum variance wavefront reconstructors. It includes correlation over time between the past history of measurements and the wind speed. The theory was initially developed without regard to computational complexity or feasibility for real-time implementation but only to provide an upper bound to AO performance of any algorithm. The resulting equations are enormously complex involving manipulation of huge non-sparse covariance matrices that become untenable at 30 meter telescope scales. With the theory in hand, in Year 7 we plan to investigate approaches using the Fourier domain to help approximate these optimum Strehl controllers with feasible amounts of real-time computation.

**Simulation tools - Arroyo:** M. Britton (Caltech) and J. Milovich (LLNL) developed a C++ class library called Arroyo to model single and multi-conjugate adaptive optics systems. Arroyo models geometric and diffractive wavefront propagation through turbulence layers and optical systems such as primary and secondary mirrors, wavefront sensors and deformable mirrors. The library is available on Arroyo’s website, [http://eraserhead.caltech.edu/arroyo/arroyo.html](http://eraserhead.caltech.edu/arroyo/arroyo.html). Establishing a close connection between realistic simulations of wave propagation through turbulence and AO system performance with analytic approaches will help us make the transition from testing reconstructors in software to applying them to experimental data. Arroyo will be used to analyze data from the Mt. Palomar Multiple Guide Star Unit (MGSU) and from the Laboratory for Adaptive Optics MCAO Test bed. The Arroyo simulation code had an initial release early in CfAO Year 5, and a major release (V1.0) at the end of Year 6. Full-up wave-optics simulations of single conjugate AO systems (e.g. Palomar and Lick) using Arroyo have been validated. Jose Milovich completed the conversion of Arroyo to a parallel processor environment and ran a series of successful tests on Livermore’s MCR machine (a 1000 node Intel processor cluster), including the fast tomography MCAO/MOAO algorithms which the CfAO has been developing.

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2.4.1.1.2. Analysis and modeling: future plans
Several members of the Analysis, Modeling, and Simulation collaboration are actively participating in the design of AO instruments for the UC/Caltech/AURA/ACURA Thirty Meter Telescope (TMT). Both MCAO and MOAO systems are in initial design phases and will heavily incorporate the lessons learned in our CfAO project. Many of the “out-year” topics are now supported through TMT and UCO/Lick Laboratory for Adaptive Optics (LAO), such as sky coverage determination given the limited number of natural guidestars, hybrid Rayleigh/Sodium laser guidestar configurations, “woofer-tweeter” configurations, and control analysis.

The Fourier domain approach has yielded insight into computationally feasible algorithms for tomography. We expect that it will yield similar results in the implementation of “Strehl-optimal” controllers that use the time history of wavefront sensor measurements along with blowing wind and boiling turbulence models to extend the control bandwidth and/or reduce the required brightness of guide star beacons.

In 2003 (CfAO Year 4), the UCO/Lick Observatory established the Laboratory for Adaptive Optics (LAO) on the UC Santa Cruz campus. This laboratory is designed to investigate concepts and technologies for the next generation of adaptive optics on present and future giant telescopes. Many of the astronomical AO concepts developed within the CfAO will be tested in the laboratory in the next few years. The LAO will also be a proving ground for the new AO component hardware, such as MEMS and the AODP-sponsored laser guide star-optimized wavefront sensor.

2.4.1.1.3. Analysis and Modeling: Partnerships with industry
Lockheed PARC AO Analysis: John Breakwell’s group at Lockheed PARC has been participating at their own expense in the CfAO modeling effort. They have investigated atmospheric outer scale effects on the PSF, and the Strehl loss due to an elongated guide star. This relationship has proven very productive. In particular the Lockheed group developed a plate-equation based model of the deformable mirror actuator influence function, which is important to optimize for best fit in a Strehl-optimizing AO system.

The Analysis and Simulation project has sponsored workshops on modeling and analysis, on an annual basis at the CfAO. We also co-sponsored a workshop on mathematical methods and adaptive optics at the UCLA Institute for Pure and Applied Mathematics (IPAM) in January 2004. Both were attended by representatives from industry, universities, and national laboratories.

2.4.1.1.4. Analysis and Modeling: Other collaborations
The Thirty Meter Telescope Project (TMT) has begun its funded design phase and needs to make major system architecture decisions in a two-year time frame. The TMT AO systems are a high-risk component, as the MCAO and MOAO concepts and associated technologies have not yet been proven on the sky in astronomical observations. Several AO system architectures, tuned to the instrument and science they service, have been proposed as concepts for TMT. Using our CfAO analysis and modeling capabilities, we have been able to provide important guidance in the development of these concepts.
CfAO Year 7, the collaboration and interaction with the TMT AO effort will continue and strengthen. Three of the senior Theme 2 collaborators (Gavel, Dekany, Ellerbroek) serve on the TMT’s Adaptive Optics Working Group.

The Laboratory for Adaptive Optics (LAO) is a separately funded component of the Lick Observatory that supports research, technology development, and education in adaptive optics. The LAO has two fundamental goals: 1) development of a prototype multi-conjugate adaptive optics system suitable for a 30 meter class telescope, and 2) development of an extreme adaptive optics planet finder instrument for an 8-10 meter class telescope. The MCAO prototype is of prime interest here, as it will be a well-controlled laboratory test of our theoretical understanding and our simulation codes. The LAO is also collaborating in projects funded by NSF’s Adaptive Optics Development Program in the areas of wavefront sensor and deformable mirror development, with some of the component tests and system integration planned to take place using LAO facilities and staff.

Lick and Palomar Observatories have working adaptive optics systems with engineering time available to provide on-sky experimental data in support of adaptive optics modeling. The system at the Lick Shane 3 meter telescope has a sodium laser guide star that is providing experience with the practical issues associated with such systems. This year, the system at the Palomar Hale 5 meter telescope will have a multi-guidestar wavefront sensor unit that will provide on-the-sky tomography data sets for concept validation of tomographic wavefront sensing. Also this year, the University of Chicago’s laser guide star will be integrated into the Palomar AO system.

2.4.1.2. Develop partnerships to co-fund long-range hardware technology development for key AO components

Several technology components are key for AO on extremely large telescopes: laser guide stars, deformable mirrors, wavefront sensors (both visible and infrared), and tip-tilt sensors. Full-up component development is costly, and is not within the CfAO’s budget profile. Hence we have chosen a few of these key technologies to emphasize, and we are doing so in partnership with other groups interested in their development. In Year 6 the CfAO has been focusing on sodium-layer laser guide star development in Theme 2, and on MEMS deformable mirror development (described in the Annual Report sections on Themes 3 and 4, and is important for Theme 2 as well)

2.4.1.2.1. Micro electro-mechanical (MEMS) deformable mirrors

Small, low cost deformable mirrors enable greatly expanded flexibility in the design of AO systems, particularly for the extremely large telescopes where ambitious demands on AO imaging performance are leading to more complex design concepts. The MOAO concept for example has one deformable mirror (DM) per science object and possibly one per laser and natural guide star, placing a premium on cost and size of deformable mirrors. Furthermore, the electrostatic actuation method used in MEMS devices provides more predictable and repeatable actuation than the piezo actuators used in conventional DMs. This enables open-loop “go-to” operation, which is central to the MOAO concept.
and the null-seeking wavefront sensor concept described previously in the section on analysis and modeling.

MEMS devices promise to scale to large numbers of actuators with much lower cost than conventional technologies, and these devices will be smaller and more precise, making them an ideal choice for high contrast extreme adaptive optics systems. For similar reasons they are attractive for applications in vision science and to the commercial ophthalmology market.

CfAO funded a number of projects developing MEMS technology in Year 6. These projects are summarized in the Theme 3 and Theme 4 progress report sections. Theme 2 did not explicitly fund ELT MEMS projects in Year 6, but has plans to do so in Year 7.

2.4.1.2.2. Guide Star Lasers

2.4.1.2.2.1. Fiber laser for sodium-layer laser guide stars

D. Pennington (LLNL) continued to make progress on a new type of sum-frequency laser based on the sum-frequency combination of light from a newly developed Nd:Silica fiber laser (NDFA) at 938 nm with that from an Erbium-doped fiber laser (EDFA) at 1583 nm in a sum-frequency crystal (SFG) as shown in Figure 2.4.1.4. This laser has now produced 2.7 watts of output power at the sodium wavelength (589 nm) in the laboratory and is expected to reach 10 watts output power by Fall 2005. The prototype 938 nm NDFA and 1583 nm EDFA lasers now produce 15 and 10 watts respectively.

The prototype fiber laser functions in continuous wave (CW) mode. Under a grant from NSF’s Adaptive Optics Development Program (AODP), the LLNL group has begun developing technologies to enable pulse formats which will mitigate the LGS spot elongation problem. Upon reaching the Year 6 output power milestone, effort will shift in Year 7 to augment the pulsed laser efforts based on the new priorities for this CfAO Theme.

![Figure 2.4.1.4 Schematic diagram of the LLNL fiber laser design.](image)
In CfAO Year 6, the group began the process of field-hardening the prototype components. The group produced a system design and cost estimate for a deployable fiber laser system. They worked with Nufern Corporation to procure a robust packaged amplifier for another project at a different wavelength. Nufern has expressed interest in producing a comparable product for 938 nm; a goal is to produce a packaged 938 nm amplifier, in collaboration with Nufern. Similar modifications will be made in the 1583 nm system.

High power fiber isolators and modulators are now available to reduce the number of free-space components between stages. Use of wavelength division multiplexers to combine the 938 and 1583 nm beams into the frequency mixing crystal was demonstrated this year. These developments will facilitate transfer of the system to a commercial partner for fabrication. Field-hardening the 938 nm laser began in Year 6 and will extend into Year 7. In Years 7/8 the commercial 1583 nm sub-assemblies currently in use will be replaced with integrated commercial components that can be inexpensively packaged in the same format as the 938 nm system.

Figure 2.4.1.5: Prototype 589 nm fiber laser in lab. Image of beam in sodium cell is used to verify 589 nm wavelength.
2.4.1.2.2. Completion of the Chicago Sum Frequency Laser and implementation at the Palomar Observatory

The Chicago Sum Frequency Laser (CSFL) developed by E. Kibblewhite (U. Chicago) consists of two pulsed, diode-pumped, mode-locked Nd:YAG lasers working at 1.064 micron and 1.32 micron wavelengths. Light from the two laser beams is mixed in a non-linear crystal to produce radiation centered at 589 nm with a spectral width of 1.0 GHz (FWHM) to match that of the Sodium-D2 line in the mesosphere. The CSFL has a micro-macro pulse format. Currently the 1.064 micron and 1.32 micron lasers produce 14 watts and 8 watts of TEM-00 power respectively. The laser runs at 500 Hz rep. rate with 10% duty cycle. This pulse format is similar to that developed by the MIT-Lincoln Labs and allows range-gating of unwanted Rayleigh scatter down to an angle of 60 degrees from the zenith. Figure 2.4.1.6 shows a diagram of the laser. The prototype laser achieved a power output of 3.5 watts in Jan 2004. Output power of 7 watts is planned by October 2005.

The laser was shipped to Palomar Observatory in July 2004, where it was installed in the Coudé room of the 200 inch telescope for use with the PALAO adaptive optics system. The 200 inch telescope has a high slenderness ratio and hence it deflects while tracking. To take out this effect and keep the laser bore-sited to its intended path, the Palomar team has implemented a low bandwidth (about 1 Hz) beam control system using motorized mirrors and quad-cells. The Palomar group also constructed an aircraft detection safety system for laser safety, and a laser launch telescope located behind the secondary mirror. The optical design of the laser launch telescope and the mechanical throw of the steering

![Schematic diagram of the Chicago sum-frequency laser](image)

Figure 2.4.1.6 Schematic diagram of the Chicago sum-frequency laser
mirror facilitate pointing the laser beam anywhere inside a field of three arc min diameter.

The first images of the beacon were obtained on April 26 2005 and are shown in Figure 2.4.1.7. The images have not yet been calibrated but it is known that the central surface brightness is the same as a 12th V magnitude star and that the beacon is about 4 arc seconds full-width half-max in size. The extensive Rayleigh backscattering will be completely gated out by the AO wavefront sensor.

![Figure 2.4.1.7. First images of the laser beacon from Palomar Observatory](image)

a) Tuned to the sodium D2 line  
b) Tuned off the D2 line  
c) Difference image. Range gating will totally suppress the Rayleigh backscattering

### 2.4.1.3. Develop techniques for doing quantitative astronomy with laser guide stars

#### 2.4.1.3.1. Point spread functions: performance, measurement, and calibration

Laser guide stars on the largest ground-based telescopes (8 – 10 meters in diameter) have only become available over the past year. Since most of the adaptive optics systems being designed for the next generation of 20 – 30 meter telescopes rely strongly on laser guide stars, it is imperative to develop and understand methods for using laser guide stars to obtain the most scientifically meaningful astronomical results.

Performance of an adaptive optics system is generally described by how well the system responds to a point source. The measured profile of an object that is supposed to be a perfect point source is called the Point Spread Function, or PSF. Accurate knowledge of the PSF is important in order to gain quantitative information such as absolute intensity measurements (photometry) and accurate positional information (astrometry) from adaptive optics images.

The overall quality of the point source response is generally described by the Strehl ratio,
which is unity for a perfect AO correction and less than unity for realistic AO systems. However, Strehl ratio measurements vary from system to system because of the different pixel sampling in the focal plane, and different algorithms used to calculate the Strehl ratio. This year we formed a “Strehl Working Group” that is addressing the nature of these existing algorithms for calculating the Strehl ratio, what are their weaknesses and strengths, and how well they work, by using simulated data of increasing complexity. Our long-term goal is to supply a menu for researchers showing how best to measure the Strehl ratio, given the characteristics of the telescope and detector being used. One of our results is a Strehl ratio calculator that is included on our software web page, http://cfao.ucolick.org/software/offsite.php.

2.4.1.3.2. Improvements to the sodium laser guide star AO system at Lick Observatory

The sodium-layer laser guide star AO system at Lick Observatory has been a facility instrument since 1998, making it the oldest such system used regularly for astronomical science. The Lick system has also been quite valuable as a test-bed for laser guide star adaptive optics observing techniques and technology development.

In order to improve the on-sky observing performance and efficiency, in Year 6 the UC Santa Cruz team lead by D. Gavel in collaboration with engineers from LLNL have undertaken a program to upgrade the tip-tilt sensor and wavefront sensor, and to improve flexure control of the laser launch telescope and diagnostics assembly. These three upgrades are significantly improving the fraction of time that astronomers actually spend observing their science targets by reducing time spent acquiring the tip-tilt star and lining up the laser beam.

The Lick Observatory tip/tilt system upgrade consisted of replacing the original quad avalanche photodiode (APD) system with a modern high quantum efficiency, low noise CCD. The 80x80 pixel CCD has greatly facilitated acquisition of dim off-axis tip/tilt guide stars and has the same signal to noise performance as good as the APD system. The new tip/tilt sensor has been installed and was tested on the sky in July 2005. Preliminary reviews by the astronomers who used the system in July were strongly enthusiastic.

The flexure control system uses a counter-flexure pointing model, computer-based lookup tables, and motor-driven pointing mirrors to compensate for the differential flexure between the science camera and tip/tilt sensor. This system was programmed and tested in 2004. With the new tip/tilt sensor upgrade, the pointing model will need to be recalibrated. The recalibration process will take place during the August 2005 engineering run at Lick, and is on track to be complete by the end of CfAO Year 6.

The wavefront sensor upgrade consists of a new CCD camera and focus stage. The new CCD has lower read noise and is smaller and lighter than the old one. The new focus stage will have more predictable motion for tracking the laser guide star’s changing focus. As of July 2005, the software for interfacing the new CCD is completed and the new stage mechanical design is complete. Tests on the sky will commence during the September-October 2005 engineering runs and are planned to be complete by the end of CfAO Year 6.
2.4.1.3.3. Improvements to the sodium laser guide star system at Keck Observatory

The first laser guide star (LGS) AO-corrected image at Keck Observatory was obtained in September 2003. Since Antonin Bouchez joined the Keck AO team in September 2003 under this CfAO project, he has contributed a great deal to the success of the following LGS AO tasks:

- Implementation and optimization of the low bandwidth wavefront sensor subsystem.
- Implementation of automated nodding and dithering for all the relevant subsystems (tip/tilt sensor stage, laser pointing mirror, FSM repositioning)
- Implementation of tip/tilt correction for the upward path of the laser
- Implementation of the diagnostics tools for monitoring the system performance

These have made the Keck laser guide star AO system a smoothly functioning science facility.

The Keck AO working group (see http://www.keck.hawaii.edu/realpublic/optics/aowg/) has worked with the Keck AO team on the milestones and priorities for the integration and demonstration of the laser guide star AO system. In the second part of 2004, subsystems have been fully integrated, and synchronous actions between subsystems have been automated, so that a baseline can be established for system performance and characterization.

A first set of performance data was collected in early 2004. The error budget was documented by identifying the main contributors using diagnostics provided by the fast wavefront sensor, STRAP tip/tilt subsystem, low bandwidth wavefront sensor, laser diagnostic tools, and images obtained with the NIRC2 infrared camera.

Engineering science observations started in April 2004. A first publication, including both the engineering science and the performance data, was presented at the SPIE in Glasgow in June 2004. One of the main goals of laser guide star adaptive optics is to be able to close the adaptive optics loop using natural stars that are much fainter than those needed for natural guide star AO (which needs stars brighter than R=13th magnitude to perform well). In August 2004, the CfAO-Keck team obtained images with a Strehl ratio of greater than 10% for a tip-tilt reference star of R=19.2 magnitude, a real milestone for adaptive optics on large telescopes. Bouchez has implemented new tools for laser guide star AO automated target acquisition. The laser guide star AO web page at W. M. Keck Observatory documents the performance of the system. It also provides LGS AO observing guidelines, and technical information for the astronomers (for more information, see http://www.keck.hawaii.edu/realpublic/optics/lgsao/)

In the fall of 2004, the first Keck LGS AO science data on the Galactic Center were released, where the motion of the stars closest to the center was used to study the black hole at the center of our Galaxy in detail. The Strehl ratio in the Lp-band (3.8 microns)

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images is greater than 73% on average for the central 10 arc sec x 10 arc sec around the massive black hole. During these initial laser guide star adaptive optics tests the team was fortunate enough to observe an Lp emission flare at the location of the Galactic Center. This data set also includes wide field (80 arc sec x 80 arc sec) laser guide star AO imaging to study the population of young massive stars around the Galactic Center. A paper has been submitted describing these results by A. Ghez and colleagues.

In addition, the Keck laser guide star AO team has been collaborating with the CATS project from CfAO to release the first laser guide star data set on the GOODS-S field. Jason Melbourne and colleagues for the CATS team have been using these data to study the merging of galaxies.

2.4.1.4. Astronomical science related to AO on extremely large telescopes

Theme 2 is sponsoring astronomical observing programs for which the scientific conclusions are dependent upon the high resolution and contrast afforded by adaptive optics. Four such programs were under way in Year 6: the CfAO Treasury Survey (CATS), a collaborative program for cataloging galaxies in the early Universe led by C. Max and D. Koo (UCSC); observing cores of nearby active galaxies, led by C. Max (UCSC), observations of planets, moons, and rings within our Solar System, led by I. de Pater (UCB); and tracking the motion of stars near the massive black hole at the center of our own Galaxy, led by A. Ghez (UCLA).

2.4.1.4.1. The CfAO Treasury Survey (CATS)

The CATS project is using adaptive optics at three 8-10 m telescopes to observe a large, deep sample of galaxies in the early universe with the goals of 1) observing the assembly of galaxies from smaller subunits to larger ones like the Milky Way, 2) measuring the rates of star formation and the evolution in stellar populations, and 3) characterizing central active galactic nuclei (AGNs) throughout the past 10-12 Billion years. CATS will disseminate an archive of forefront AO data and associated reduction and analysis tools, as a community resource.

CATS is planned to last through all of the 2nd five years of CfAO, and to focus on the largest Hubble Space Telescope (HST) fields designed for faint galaxy surveys. These presently include two GOODS (Great Observatories Origins Deep Survey) fields (North

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and South), the GEMS field (an extension of GOODS-S), COSMOS (an equatorial field), and one of the four DEEP fields known as the Extended Groth Strip. These regions of the sky are being intensively studied by the world's most powerful ground and space telescopes, spanning energies from radio to X-rays. All are expected to produce their deepest images to date. CATs will provide near-infrared images, a critical missing wavelength range, at a resolution (0.05 arcsec) comparable to the optical diffraction limit of HST. The near-IR is particularly valuable because it penetrates dust-obscured regions, is sensitive to old stars, and, for high-redshift objects, measures light that was emitted as visible photons, allowing direct comparisons to extensive optical studies of local galaxies. CATs will require dozens of Keck, Gemini, and Subaru observing nights, with significant repeat observations to reach fainter limits, gain larger fields of view, and detect variable AGN and supernovae. Measurements of kinematics and spectra at high spatial resolution in the near-IR will begin during the coming year with the OSIRIS integral field spectrograph (led by co-PI Larkin) on the Keck Telescope.

From fall 03 through spring 05, the CATS team was awarded 10.5 nights of Keck natural guide star AO time and 4.5 nights at Keck for spectroscopic follow-up. In fall 04 and spring 05 the team was awarded a night of laser guide star (LGS) AO time on Keck, from which a paper in the Astrophysical Journal Letters has been published. Most importantly, the team was awarded 4.5 nights of Keck laser guide star AO time for fall 05, representing 45% of the total University of California allocation of laser guide star AO time. The CATS team initiated a plan with Dr. Fred Chaffee, Director of Keck Observatory, to obtain non-AO optical redshift data in the GOODS-North field in spring 2003; these data were released to the astronomical community in 2004. The Space Telescope Science Institute has agreed to collaborate in developing a CATS public archive and database.

![Fig. 2.4.1.8](image)

**Fig. 2.4.1.8** An example of CATS data: This NIRC2 image is an hour exposure taken in Mar 2005 with the Keck laser guide star AO system. The field is located in the Extended Groth Strip where HST ACS and NICMOS-3 images exist. The right hand panel is a blow-up of one galaxy and shows the superior spatial resolution in the near-IR achievable with the Keck AO system (resolution of 0.05 arcsec) compared to the HST NICMOS-3 image. Such AO resolutions allow unique studies of small subcomponents within distant galaxies, such as bulges (see example below the marked galaxy), bars, AGNs, and supernovae.
2.4.1.4.2. CATS: Current status and technical challenges

Keck laser guide star system

We have had spectacular success with our laser guide star time this year. The long-term success of CATS will rely on the Keck Observatory providing a consistent and efficient laser guide star AO system on Keck. The laser guide star is needed to provide larger areal coverage in the HST fields that are part of the CATS program, and to gain experience in high-redshift science that links CATS to the science case for Extremely Large Telescopes. For Fall 2005, Keck plans an intensive laser guide star AO campaign, and CATS was fortunate to be awarded 4.5 nights. Whether adequate amounts of LGS AO time will be available in future seasons for our Year 7 to Year 10 programs is as yet unknown. CATS can fortunately work with natural guide star AO as well, since its primary fields cover 5000 square arc min, large enough to provide plenty of natural guide star targets. By Year 9 of the CfAO it is likely that an additional new laser guide star will be available on the Keck I telescope.

Point Spread Function (PSF) Characterization

This is a challenge for both natural guide star and laser guide star AO. Progress is being made. Until the Keck laser guide star system has been characterized more extensively and additional modes of operation are developed (e.g., wavefront sensor telemetry data during AO observations), the real-world utility of various PSF measurement methods will be developed and tested primarily within the CATS program.

Parameter Error Analysis from AO Data

Given the uncertainty and time variability of the PSF during AO observations, the effect on errors of derived parameters (e.g., fluxes for bulges or supernovae subcomponents embedded in a bright host galaxy, colors and radial light profiles from different AO images, astrometric positions of fuzzy objects) are not well known. A goal of the CATS project is to improve reduction and simulation software and a library of AO PSFs to explore this issue. The knowledge and experience gained will be part of the legacy deliverables from the CATS program for the broad astronomical community.

2.4.1.4.3. Active galactic nuclei

Max and collaborators (UCSC) are using the existing laser guide star adaptive optics systems at Lick and Keck Observatories to study nearby galaxies having active black holes in their nuclei, and comparing their cores with the nuclei of "normal" galaxies. They are characterizing differences on spatial scales smaller than a kiloparsec between galaxies where the black hole is actively accreting matter ("active galaxies") and those with little or no level of black hole activity. What is new and different about this work is

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its comprehensiveness: the goal is to combine imaging information in the near-infrared (from adaptive optics and from the Hubble Space Telescope, HST) and in the visible (from HST) with spectroscopy of molecular gas (from infrared adaptive optics) and atomic gas (from STIS on HST). This suite of new data is allowing the team to study morphology and kinematics of the dust and of the gas in these galaxies, and to correlate the results with the galaxies’ light profiles. They are using colors measured from HST and ground-based adaptive optics to derive the ages of star clusters near the centers of these galaxies. They are also exploring the relationship between rotation curves and spiral structure in the nuclear regions, in order to clarify the role of nuclear spiral structure in galaxy activity.

During the first quarter of Year 6 graduate student Lynne Raschke finished data collection at Lick Observatory and completed nearly all of the data reduction. Raschke also completed data reduction of HST images for objects having Lick AO data.

Raschke then turned her attention to a particularly interesting galaxy in her sample, IC 342, which she and her advisors had selected for the first journal article to be submitted based on her dissertation work. IC 342 is a nearby 17 late-type spiral galaxy with significant nuclear star formation. The center of IC 342 contains a number of bright star clusters. Previous work using ground-based near-IR imaging and spectroscopy and HST images determined the age of the brightest, central-most cluster to be about 60 Myr and the mass about $6 \times 10^6 \, M_\odot$. Raschke’s Lick laser guide star AO images are much higher resolution than previous work in the near-IR. She analyzed the narrowband Br $\gamma$ images and developed a routine for properly subtracting the continuum, leaving only flux due to emission lines. Raschke is continuing to work on the photometry of the many clusters in the central regions of IC 342. Included in this work is a study of the effects of the AO point spread function on the photometry results.

Also within the scope of this project, Claire Max continued her studies of the disk-galaxy merger pair NGC 6240. She completed a first journal article based on both Keck adaptive optics data and Hubble Space Telescope NICMOS infrared data,18 showing that the 10-m Keck telescope with its current adaptive optics system has better spatial resolution than Hubble at a wavelength of 2.2 microns (K band), whereas Hubble’s NICMOS camera (NIC2) has better spatial resolution in the 1-micron region (J band). This is

Figure 2.4.1.9. The central 2 kpc of NGC 6240, an ongoing merger of two disk galaxies. Frames a), b), and c) are Keck AO images at J, H, and Kp bands respectively. Frames d), e), and f) are Hubble NICMOS images at the same wavelengths. The spatial resolution of Keck AO is superior at Kp band, frames c) and f), whereas Hubble is superior at J band, frames a) and d).
illustrated in Figure 2.4.1.9. A second paper identifying the positions of the two black holes in the core of NGC 6240 is in the final stages of preparation, and will be submitted to *Science*.

Max and LLNL scientist Seran Gibbard have completed their work on a survey of nearby active galactic nuclei (redshifts z<0.1); they studied the surface brightness profiles and quantitative morphologies of 12 AGNs. A journal article will be submitted for publication before the end of Year 6.

### 2.4.1.4.4. Solar System Planetary Science

Over the past years, the team led by I. de Pater (UC Berkeley) acquired data with several of the currently available AO systems (Keck, ESO-VLT, Gemini, Lick, and ESO-3.6 m) using several different observing modes (imaging in narrow band filters, spectroscopy, and LGS imaging) on Titan, Neptune, Uranus, Io, Jupiter's ring and Callisto, binary asteroids and transneptunian objects (TNOs). In addition to their scientific value, the images have had tremendous public appeal.

The observations of Titan, Saturn’s largest moon, provide infrared maps of the 3-dimensional distribution of haze in Titan's atmosphere, as well as its surface albedo and the presence of tropospheric clouds, addressing questions regarding seasonal variations in Titan's atmosphere and the composition of its surface (are there liquid hydrocarbons?). Ongoing monitoring of volcanoes on Jupiter’s volcanic moon Io again witnessed that Io is extremely active: each observation in the Keck AO monitoring program reveals surprisingly different surface features, due to new volcanic eruptions.

Images of Uranus' atmosphere and ring system are among the best ever taken. They

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**Fig. 2.4.1.10:** a) - c) Keck AO image of Uranus at 2.2 micron, after combining all data from July 3-9 2004. The entire image is shown in panel a); panels b) and c) show the north and south ansae, respectively. The individual ringlets are indicated; the innermost ring is 1986 U 2R, which has not been seen since the Voyager fly-by of Uranus. (de Pater, Gibbard, and Hammel, 2005, submitted to Icarus). d) A single image in H and K’ band, revealing a Southern hemisphere feature in K’ (circled), indicative of vigorous atmospheric convection.
detected a sheet of material interior to the widely known rings of Uranus, which coincides with the ring 1986 U 2R, seen only once before in a Voyager forward-scattered image (Figure 2.4.1.10). Cloud features in Uranus' northern hemisphere (just emerging from a decades-long darkness) suggest the beginnings of a polar collar.

![Fig. 2.4.1.11. First Triple Asteroid ever discovered. The dashed lines correspond to the orbits of the two moonlets. This image is a composite of 9 individual observations taken on 9 nights and high-pass filtered via the "unsharp masking" technique. North is up and East is left. The inset shows the primary asteroid’s shape after deconvolution. (Marchis et al, to be published)](image)

The Berkeley group has discovered unique and puzzling atmospheric circulation on Neptune by tracking individual cloud features on this most distant giant planet. Impressive Keck AO images of Neptune's ring-arc system document its continuing change since the Voyager era, and improvements have been made to Neptune's satellite ephemerides based on the astrometric analysis of Keck AO images. The group has further observed a multitude of asteroids and Trans-Neptunian Objects in their search for binary systems with a variety of telescopes/AO systems. They detected the first ever triple asteroid system, a discovery that undoubtedly will trigger renewed observational campaigns and theoretical studies to explain such systems (Figure 2.4.1.11). They have further made a detailed comparison for several asteroids between the shape of an asteroid as derived from AO and that derived from conventional light-curve data (Figure 2.4.1.12).

![Fig. 2.4.1.12 The asteroid 130 Elektra observed with the Keck AO system in K band [left]. Elektra is quite irregular in shape, with a non-uniform albedo. On the right is shown its shape as derived from light-curve inversion techniques. (Marchis et al 2005)](image)
The massive black hole at the center of our Galaxy

The center of our Milky Way Galaxy is now known to contain a black hole with mass more than three million times the mass of the Sun, and thus represents a very nearby opportunity for studying the physics and astrophysics of black holes in galaxy cores. Technically, the Galactic Center presents challenges that range from observational, due to the lack of a bright natural guide star at optical wavelengths, to analytical, due to the crowded stellar field at near-infrared wavelengths. A. Ghez and colleagues (UCLA) therefore are studying Adaptive Optics performance on this field with a variety of different systems (Keck vs. Gemini; natural guide star vs. laser guide star) from the point of view of point spread function quality, overall Strehl, stability, and anisoplanatism. In addition they are investigating the astrometric and spectroscopic accuracies that can be achieved in such a crowded stellar field. These technical results will be of strong interest to the general astronomical community.

Astronomically, Ghez et al. are studying the environment of the Galaxy's central supermassive black hole to measure the dynamics, distribution, and properties of the stars in the central stellar cluster. Spectroscopy and imaging have allowed them to obtain the most accurate and precise estimate of the distance to the Galactic Center, to constrain the dark mass distribution at smaller radii than ever before (with special focus on what might surround the central black hole), to improve studies of possible counterparts to Sgr A* (the radio source at the location of the black hole) at near-infrared wavelengths, and to resolve the paradox of apparently young stars in an environment that is currently quite hostile to star formation, given the strong tidal forces presented by the black hole and the low gas densities in its vicinity.

In Year 5 the UCLA group discovered a variable point source, imaged in the L’ band (wavelength 3.8 microns) with the Keck II telescope's adaptive optics system, that is coincident to within 18 milli-arc sec (1σ) of the Galaxy's central supermassive black hole and the unique radio source Sgr A* (see Figure 2.4.1.13). While in 2002 this source (SgrA*-IR) was confused with the stellar source S0-2, the two sources had separated by 87 milli-arc sec in 2003 because S0-2 had moved relative to Sgr A*. This enabled the

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<td><img src="image1" alt="SO-2" /> SgrA*-IR</td>
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<td><img src="image3" alt="SO-2" /> SgrA*-IR</td>
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Figure 2.4.1.13. Three images at 3.8 micron wavelength of the infrared counterpart of SgrA*, at the presumed location of the black hole in the core of the Milky Way Galaxy. Each image is about 0.6 arc sec on a side.
new source's properties to be determined directly. On four separate nights, its observed L' magnitude varied from 12.2 to 13.8, which corresponds to a dereddened flux density range of 4 - 17 mJy; no other source in this region shows such large variations in flux density — a factor of 4 over a week and a factor of 2 over 40 min. In addition, it has a (K-L') color greater than 2.1, which is at least 1 magnitude redder than any other source detected in the L' wavelength band in its vicinity. Based on this source's coincidence with the Galaxy's dynamical center, its lack of motion, its variability, and its red color, the UCLA group concluded that it is associated with the central supermassive black hole. The short timescale for the 3.8 micron flux density variations implies that the emission arises quite close to the black hole, within 5 AU, or 80 Schwarzschild radii. It is likely that both the variable 3.8 micron emission and the X-ray flares arise from the same underlying physical process, possibly the acceleration of a small population of electrons to ultrarelativistic energies. In contrast to the X-ray flares which are only detectable ~2% of the time, the 3.8 micron emission provides a new, constantly accessible, window into the physical conditions of the plasma in close proximity to the central black hole.

Photometry of all the sources detected in the L' band in maps obtained at Keck has been carried out, along with photometry in high angular resolution maps in the K-band (Keck) and H-band (Gemini-AO). These data have been combined in color-magnitude and color-color plots to derive extinction along the line of sight to the Galactic Center (slightly lower than previous estimates) and to identify high mass-loss-rate stars.19

Ghez et al. have gone back to older AO images and carried out a complete re-analysis of all their existing data (improved frame selection, improved imaging weighting, and improved re-sampling). This analysis has yielded much more sensitive maps, and the discovery of a source near the location of the black hole in these older images. Within 0.4 arc sec of the Galaxy's central dark mass, Ghez et al. identified 22 stars with measurable proper motion, with K magnitudes ranging from 13.9 to 17.7; 15 of these are new detections. In this sample, three newly identified (S0-16, S0-19, and S0-20) and five previously known (S0-1, S0-2, S0-3, S0-4, and S0-5) sources have measured proper motions that allow orbital solutions around the black hole. A simultaneous solution pinpoints the Galaxy's central compact dark mass to within ±1 milli-arc sec and, for the first time from orbital dynamics, limits its proper motion to 0.8 ± 0.7 milli-arc sec/year.

The estimated central dark mass from orbital motions is \((4.0\pm0.3) \times 10^6 (R_0/8 \text{ kpc})^3 M_\odot\). The smallest closest approach is achieved by the star S0-16, which confines the central compact dark mass to within a radius of a mere 90 AU and increases the inferred dark mass density by four orders of magnitude compared with earlier analyses based on velocity and acceleration vectors. These adaptive optics data make the Milky Way the strongest existing case by far for a supermassive black hole at the center of any normal type galaxy.

One of the most perplexing problems associated with the supermassive black hole at the

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center of our Galaxy is the origin of the young stars in its close vicinity. Using proper motion measurements and stellar number density counts based on 10 years of diffraction-limited K (2.2 µm)-band imaging at Keck, Ghez et al. have identified a new comoving group of stars, which they call the IRS 16SW comoving group, located 1.9” (0.08 pc, in projection) from the central black hole. Four of the five members of this comoving group have been spectroscopically identified as massive young stars, specifically He I emission line stars and OBN stars. Based on its dynamical association, the remaining group member is postulated to be a young star. This is the second known young comoving group within the central parsec of the Milky Way and is the closest, by a factor of 2, in projection to the central black hole. These comoving groups may be the surviving cores of massive infalling star clusters that are undergoing disruption in the strong tidal field of the central supermassive black hole

The Galactic Center is a difficult AO target: it is at high airmass as seen from the telescopes in Hawaii (such as Keck), and has no bright star nearby to use as a wavefront reference. The UCLA group plans to explore the trade-offs between different natural guide stars, optical and infrared-wavefront sensing, and natural guide star vs. laser guide star AO operation. They will also explore a second type of trade-off, between integration time and point spread function (PSF) quality. Shorter exposures tend to produce higher Strehl images, but are obtained much less efficiently, in terms of telescope time. This trade-off affects the number of sources that are detectable, the photometric and astrometric accuracies for the detected point sources, as well as the sensitivity to extended structures. For instance, while deeper images increase the signal to noise ratio for the brightest stars and reveal fainter isolated point sources, the longer exposures have poorer image quality, affecting the ability to measure the faint stars that are nearby bright stars due to spill-over (larger halos) from the bright stars. This work has begun by comparing the Keck and Gemini AO images, which have very different exposure times and Strehls.

A related and important component of this work is point spread function reconstruction. In a crowded field such as that of the Galactic Center, astrometric and photometric accuracies as well as sensitivities to faint point sources and extended structures are affected not only by the Strehl, but also by our ability to reconstruct the PSF. Collaboration between Julian Christou (UCSC) and Andrea Ghez (UCLA) is critical to the success of this aspect of the program. The current analysis of existing data shows that quantitative conclusions are limited by the quality of PSF reconstruction. Collaborative work this past year has dramatically increased sensitivity to faint sources in the crowded central region and improved the astrometric precision.

While the above work focuses on imaging, AO now allows spectra as well. The arrival at Keck of the OSIRIS integral field AO spectrograph will enable the study of the above trade-offs for spectroscopy, with the additional parameter of spectral resolution to consider.

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2.4.2. Theme 3: Extreme Adaptive Optics (ExAO): Enabling Ultra-High Contrast Astronomical Observations

2.4.2.1. Introduction

Extreme Adaptive Optics (ExAO) focuses on the development and utilization of precision AO systems and instrumentation to enable ultra-high-contrast astronomical observations. The primary goal is the discovery and characterization of extrasolar planets through direct imaging, thereby providing new insights into planet properties and formation. Commencing in Year 4, members of the ExAO theme set out to accomplish this by proposing an ambitious, highly collaborative, multi-institutional, long-term project that included scientific and technological components. The objective is deployment of a dedicated ultra-high-contrast system for an 8-10 meter telescope capable of imaging self-luminous, extrasolar planets at contrast levels $> 10^{-7}$.

In Year 5, a design study for the eXtreme AO Planet Imager or XAOPI, appropriate for the Keck Telescope, was completed. The design study included development of key technologies such as the efficient Fourier Transform Reconstructor and the Spatially Filtered Wavefront Sensor, as well as an error budget methodology and an overall system architecture. Subsequently, the CfAO team competed for and was awarded a contract from Gemini Observatory in support of a design study for a similar instrument - the Extreme AO Coronagraph (ExAOC), for one of the Gemini telescopes. The CfAO design team expertise was significantly augmented by partnerships with institutions in the US and Canada.

During Year 6, the partnership completed the Gemini ExAOC design study and presented to Gemini a comprehensive, four-volume conceptual design report and a proposal for construction of the instrument. The review was extremely positive; we are currently waiting for a final decision on construction. Selection of our team will result in the CfAO being responsible for the most advanced adaptive optics system ever deployed. In addition, a CfAO team has participated in the definition of an ExAO instrument for the Thirty Meter Telescope, using models to identify the unique science niches for a ground-based ELT in the era of interferometers and spacecraft such as the Terrestrial Planet Finder. Based on this work, our team successfully proposed and was awarded a contract to study the feasibility of Planet Formation Imager, an instrument that exploits the high angular resolution of a ground-based ELT to access phase space inaccessible to smaller telescopes.

Our plans for Year 7 are contingent on whether Gemini Observatory will fund construction of the ExAOC system. On the assumption that this project proceeds, the CfAO will support efforts in the areas of performance simulation and science case development for the Gemini instrument. These basic research activities are beyond the scope of the Gemini instrument construction project, and will optimize the ability of the scientific community to utilize this instrument. In addition, we will continue to support efforts on risk reduction and the study of key technologies for ExAO: MEMS properties, wavefront sensing and reconstruction without systematic errors, optimal coronagraph architectures, and precision wavefront calibration. We will continue to demonstrate some
of these technologies in the Laboratory for Adaptive Optics at UCSC, and we will begin demonstrating others at JPL and the American Museum of Natural History. We will continue ongoing programs in high-contrast observations at Lick and Keck observatories.

The ExAO theme takes explicit advantage of the “Center mode of operation,” since its project is significantly larger in scope and duration than a typical NSF single PI project, and can only be accomplished by coordinating and combining the efforts of numerous researchers at multiple institutions. Developing the key enabling technologies for an ExAO system necessitates multi-disciplinary collaborations, including links to engineering researchers and industrial partnerships. Development of key enabling technologies also strengthens links between astronomy and vision science. For example, MEMS deformable mirrors are being developed for both applications, and current AO system performance optimization activities address both astronomical and vision science systems. Finally, design and implementation of an ExAO system with $10^3$-$10^4$ degrees of freedom on the current generation of large telescopes is an important step towards AO for extremely large telescopes, which requires a similar number of control points.

2.4.2.2. ExAO Theme Accomplishments

2.4.2.2.1. High-contrast science with current AO systems

The team led by Andrea Ghez at UCLA is continuing to probe two aspects of star and planetary system formation. First, it is performing high contrast imaging on young stars known to host either a circumbinary or edge-on circumstellar disk. Obtaining a resolved scattered light image at 3-5 µm of these disks will enable pinpointing the presence of dust grains that are larger than those found in the interstellar medium. This would provide direct evidence of grain growth in circumstellar disks, the first stage of planet formation. Second, the team is conducting high spatial resolution imaging and spectroscopic observations of close, young low-mass binary stars. This work is now yielding its first orbital solutions, its overall goals being the calibration of pre-main sequence evolutionary models across the stellar-substellar boundary and the verification of the mass of several candidate substellar companions.

The first shared-risk science night at Keck using the laser guide star in conjunction with the AO system was devoted to the imaging of disks in scattered light. Several objects were successfully observed with Strehl ratios of 0.75 at wavelengths of 3.8 and 4.7 microns. These data were combined with data previously collected using the Keck AO system in natural guide star configuration. Analysis of these data sets shows that circumstellar disks around three objects have been spatially resolved in scattered light in the 3-5 micron wavelength range. Furthermore, the angular dependence of scattered light at these wavelengths does not behave as expected from standard interstellar medium dust models: the disks consistently show evidence for more forward-throwing dust at longer wavelengths. Multi-wavelength Monte Carlo modeling of these systems finds evidence for larger than ISM grain sizes and, in at least two of these cases, evidence for dust settling.

The team led by James Graham at UC Berkeley is continuing a program of observing debris disks around nearby stars with AO and a survey of Herbig Ae/Be stars using Lick
AO polarimetry. Asymmetric structure detected in dusty debris disks may be associated with dynamical perturbations due to giant planets. With the Keck AO system, Kalas and Fitzgerald have observed the newly discovered debris disk AU Microscopii (Kalas et al. 2004). See Figure 2.4.2.1.

Figure 2.4.2.1: NIRC2/AO coronagraphic J, H, and K composite image of the edge-on disk surrounding AU Mic obtained on August 30, 2004 (Fitzgerald, Kalas & Graham 2005) emphasizing the midplane sub-structure, including significant deviations in vertical symmetry. The AU Mic disk is detected near the edge of the 5” radius field of view, where the disk surface brightness is approximately $H = 18.5 \text{ mag arc sec}^{-2}$. Remarkably, the disk is detected as close as 1” radius, which corresponds to a distance of 10 AU from the parent star.

The Lick AO polarimetry survey of Herbig Ae/Be stars has continued with great success (Perrin et al. 2004). In 2004, the Berkeley team had three observing runs, in July, September, and October; the July and especially September runs had spectacular seeing and they were able to make good progress in the survey. They have now observed 90 targets (including 80% of summer and early fall targets), with resolved polarized scattered light detected around 17. Their observations are the first high-resolution observations for many of these sources, e.g., Parsamian 21 & 22, V645 Cyg, PDS 465 and 581. But the most exciting result is the discovery of an edge-on disk around the northern star in PDS 144.

Figure 2.4.2.2: PDS 144. This disk was discovered in Lick polarimetry observations on 2004 July 5, and rapidly followed up at Keck with AO and mid-IR images on 2004 August 28-30. It is the first known optically thick edge-on disk around a Herbig Ae star and is likely the precursor of a Vega-like debris disk system.

2.4.2.3. Gemini Extreme Adaptive Optics Coronagraph (ExAOC)

In Year 6, a science-driven design of a technically feasible ExAO instrument for Gemini was completed and a four-volume conceptual design report produced. The primary Year 6 milestone for the Theme was the Gemini Conceptual Design Review, which occurred in
March 2005. The review response was extremely positive and the final decision from the Gemini Board is pending.

The Gemini ExAOC design study ran from about June 2004 to February 2005. Gemini provided ~$200K for the study, which was insufficient for a detailed conceptual design for a ~$20M instrument which is well beyond the current state of the art. Consequently the Laboratory for Adaptive Optics (LAO) at UCSC co-funded the Gemini effort, and CfAO funding was used to support distinct but complementary goals. The bulk of the direct Gemini funding was used to support institutions not already part of our CfAO ExAO efforts – the Hertzberg Institute of Astrophysics (HIA), and the Université de Montréal, as well as the American Museum of Natural History (AMNH).

Below is a summary of activities at each CfAO institution:

- LLNL (CfAO and LAO funding): Completed development of AO control algorithms and realtime software architecture, project management and leadership. Demonstrated high-contrast imaging goals using MEMS mirrors and realistic aberrations on LAO testbed.
- UC Berkeley (CfAO funding): Completed development of a quantitative ExAO science case, accomplished high-contrast science with Lick and Keck AO systems
- STScI (CfAO funding): Completed design of a ExAO coronagraph suitable for a circular-aperture telescope. Design of coronagraphs for segmented telescopes. Laboratory testing at LAO of coronagraph concepts.
- JPL (CfAO funding): Designed an ExAO calibration architecture and verified its performance in simulation. Preliminary testing of calibration architecture at JPL, Palomar, LAO.
- UCSC (LAO funding): Supported high-contrast experiments on the LAO ExAO testbed.
- UCLA (CfAO funding): High-contrast science with Keck AO including Keck laser guide star.

2.4.2.3.1. ExAOC system overview

Imaging most exoplanets requires contrast vastly better than that delivered by existing astronomical AO systems. Currently achievable contrast, about $10^{-5}$, is limited by quasi-static wave front errors, so that contrast does not improve with integration times longer than about 1 minute. Moreover, there are enough slow drifts in these wave front errors that PSF subtraction does not increase contrast by very much, except in the most ideal circumstances. ExAOC will surpass the performance of existing systems by two orders of magnitude in contrast ratio – an improvement comparable to the transition from photographic plates to CCDs. This may sound daunting, but other areas of optical science have achieved similar breakthroughs, for example, the transition to nanometer-quality optics for extreme ultraviolet lithography, the development of MEMS wavefront control devices, and the ultra-high contrast demonstrated by JPL’s High Contrast Imaging Test-bed. The Gemini ExAOC project will be the first project to apply these revolutionary techniques to ground-based astronomy.

Macintosh, Graham and their team used the Monte Carlo method to select the primary observing wavelength, subaperture size, and AO loop bandwidth for the baseline ExAOC
system presented in their Gemini conceptual design proposal. The final adopted system has 44 subapertures ($d = 18$ cm diameter) across the 8-m primary, a maximum frame rate of 2.5 kHz, and a WFS read noise is 8 e$^-$ rms. A Blackman window approximates an apodized pupil Lyot coronagraph architecture. The atmosphere is modeled with two layers (0 & 4 km), each with independent wind velocity vectors. The wave front reconstructor uses adaptive modal gain control. Figure 2.4.2.3 shows the rms speckle noise at H band (1.6 micron) as a function of radius for bright and dim guide stars for atmospheres representative of Mauna Kea and Cerro Pachon. These curves show a characteristic dark region between about $3\lambda/D$ (0.12 arc seconds) and the AO control radius at $\lambda/2d$ (0.9 arc seconds). The speckle noise is measured in units of the stellar flux. Thus, these curves represent the achievable contrast ratio, neglecting photon shot noise from the uncorrected stellar halo and sky or detector noise.

![Figure 2.4.2.3: The 1-$\sigma$ speckle noise at H for the system adopted for the Gemini conceptual design with 18-cm subapertures and a maximum update rate of 2.5 kHz. The integration time is one hour. The speckle noise is measured in units of the guide star brightness. These curves represent the achievable contrast when speckle noise is dominant. System performance is a function of guide star magnitude (thick vs. thin lines). The Fried parameter for Mauna Kea is 18.7 cm and 14.5 cm for Cerro Pachon.](image)

![Figure 2.4.2.4: The distribution of atmospheric properties of 121 Gemini ExAOC detected exoplanets from a hypothetical survey of the solar neighborhood. Solid lines show the evolution of exoplanets ranging from 1–20 MJ (Burrows et al. 2003). Dotted lines are isochrones labeled in log10(Gyr). The detected planets (filled circles) are drawn from a field survey of nearby (< 50 pc) stars (no age cut). The population straddles the H2O cloud condensation line at about 400 K (dashed), and a few objects lie below the NH3 condensation curve (dashed). The speckle noise suppression factor is 1/16, and the Cerro Pachon atmosphere is assumed. The only known astronomical object that lies on this plot is Jupiter, with $T_{\text{eff}} = 120$ and log10$g = 3.4$.](image)
One way to visualize how baseline Gemini ExAOC system explores exoplanet phase space is to plot the detected planets on an effective temperature, log g diagram. The results of a hypothetical survey of the solar neighborhood are shown in Figure 2.4.2.4. The youngest detected exoplanets have ages of a few hundred Myr, representing the youngest systems in the sample (the properties of younger planets depend on initial conditions, and have not been included in the Monte Carlo simulations). The youngest detections include masses as low as 1 M_J. With increasing age, the mean detected planet mass increases. The median exoplanet age is 1.3 Gyr, the oldest have ages of ~ 5 Gyr. About 70% of the planets are cooler than the water cloud condensation line, but only three lie to the left of the ammonia cloud condensation curve.

To achieve this performance, the ExAOC system consists of five key subsystems (Figure 2.4.2.5) held together by the opto-mechanical superstructure:

1. The AO system is responsible for fast measurement of the instantaneous wave front, and for providing wave front control via deformable mirrors (LLNL);
2. The calibration unit provides precise and accurate measurements of the time-averaged wave front at the science wavelength, so that the final image is not dominated by persistent speckles caused by quasi-static wave front errors (JPL);
3. The coronagraph uses a combination of apodized masks and focal-plane stops to control diffraction and pinned speckles (AMNH);
4. The science instrument—an integral field unit (IFU)—produces the final scientific image or data cube, including simultaneous multiple wavelength channels to suppress residual speckle noise (UCLA); and
5. The upper-level software coordinates communication between subsystems and between ExAOC and the observatory software (HIA).
The entire system is housed in an Opto-Mechanical superstructure (OMSS) that mounts the optics for the AO system and coronagraph, holds the IFU and calibration system in place, interfaces to the telescope, and also seals the instrument against outside conditions. A more concrete view of the ExAOC system is depicted in Figure 2.4.2.6. Table 2.4.1 lists the key parameters of the system.

**Figure 2.4.2.6**: Overview of Gemini ExAOC system with its covers removed and the external support frame hidden. F/16 light from the secondary exits from the Gemini ISS and is collected by a pointing and centering pair, which steer the beam to the right towards the first AO relay. This contains the “woofer” bimorph deformable mirror (DM), which is responsible for controlling low-order modes. The second AO relay illuminates the high-order MEMS DM at the center of the optical bench, from where the light is handed off to the coronagraph section, which occupies the bottom of the optical bench. Corrected light is then split between the calibration unit and the science instrument (IFU).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subaperture Size</td>
<td>18 cm (1528 subapertures)</td>
</tr>
<tr>
<td>Deformable mirror</td>
<td>4096-actuator MEMS</td>
</tr>
<tr>
<td>AO Update rate</td>
<td>2500 Hz</td>
</tr>
<tr>
<td>Coronagraph</td>
<td>Apodized-Pupil Lyot Coronagraph</td>
</tr>
<tr>
<td>Coronagraph inner working distance</td>
<td>0.09 arcseconds at H</td>
</tr>
<tr>
<td>Science Instrument</td>
<td>1-2.5 m integral field unit</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>0.014 arc seconds</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>$R=40$ at H band</td>
</tr>
</tbody>
</table>

**Table 2.4.1**: Key parameters of the Gemini ExAOC design.
2.4.2.3.2. Future Plans

The cornerstone of the CfAO ExAO theme is the construction and deployment of an operational high-contrast AO system for the discovery of extrasolar planets. We have completed a detailed conceptual design for such an instrument, the Extreme Adaptive Optics Coronagraph (ExAOC) for the Gemini Observatory. If the instrument is selected by Gemini, we will begin the detailed design and construction phase. During this phase, the CfAO will support the basic research and development needed to enable this instrument. At LLNL, CfAO will fund development of advanced wavefront control algorithms suitable both for ExAOC and future ELT AO systems. At UC Berkeley, CfAO will fund Project Scientist James Graham in development of the ExAOC science case and planning for ExAOC science operations. At AMNH, Anand Sivaramakrishnan and Ben Oppenheimer will construct a test bed for development of advanced coronagraph masks. At JPL, Kent Wallace will develop and prototype an advanced interferometric wavefront sensor. CfAO will provide coordination of the different institutions involved and connections to the broader astronomical community, and will organize workshops.

Our strategy in this Theme is to support fundamental research and development activities required to enable the deployment of an ExAO system on an 8-10 meter telescope, with construction provided by an external source. Due to the opportunistic nature of this strategy, the specific plans for our ExAO efforts have had to be adapted to changing external circumstances – most notably the opportunity to build a Gemini instrument, which (for the construction phase) would be almost fully funded by Gemini itself. There is uncertainty inherent in these opportunities and thus, our plans for Year 7 and beyond are contingent on Gemini selection of ExAOC. Selection and full funding by Gemini will be a major outcome for the CfAO ExAO effort. It will allow us to carry ExAO forward, and free up funding for new ExAO areas such as TMT, innovative wavefront sensing concepts, etc. If we are not selected, we will ramp our Gemini-related activities down to zero, and will instead pursue funding for ExAO at Keck or other telescopes; a determination on this will be made before the beginning of Year 7.

2.4.2.4. ExAO for Extremely Large Telescopes

In addition to the 8-m class ExAOC design, the ExAO theme has begun thinking about requirements for Extremely Large Telescopes. During Year 6 we participated in the definition of the ExAO instrument for the Thirty Meter Telescope, using models to identify the unique science niches for a ground-based ELT in the era of interferometers and spacecraft such as the Terrestrial Planet Finder. Based on this work, our team successfully proposed and was awarded a contract to study the feasibility of a Planet Formation Imager for the Thirty Meter Telescope, an instrument that exploits the high angular resolution of a ground-based ELT to access phase space inaccessible to smaller observatories. During Year 7 we will work on the basic concepts needed for ExAO on 20-30 m telescopes. Key areas include refinement of the science case for ELT ExAO, development of coronagraphs suitable for large segmented apertures, and research into advanced technologies such as predictive controllers and interferometric infrared wavefront sensors that will enable next-generation ExAO.
2.4.3. **Theme 4: Vision Science**

2.4.3.1. **Introduction**

Scientists and engineers participating in the Vision Science Theme have agreed to focus their efforts on the development of ophthalmic instrumentation equipped with AO, with the ultimate goal of commercialization. Ultimately, broad accessibility requires the development of low-cost, compact, and robust devices that can be used by clinicians who are unskilled in adaptive optics. The development of inexpensive, small, and high stroke deformable mirrors is critical to achieving broad dissemination of the technology. CfAO has undertaken to support four groups working on new deformable mirror technologies. Investigators in Theme 4 continue to produce new demonstrations of the scientific value of adaptive optics in understanding normal vision and retinal organization. Furthermore, all groups building AO instruments in this theme are exploring the value of adaptive optics in the diagnosis and treatment of retinal disease.

2.4.3.2. **Instrumentation**

CfAO has stimulated the development of at least 7 AO systems for vision science since its inception, a remarkable achievement. These devices reside at the University of Rochester, Indiana University, UC, Berkeley (formerly U. Houston), and UC Davis (the latter constructed in collaboration with Lawrence Livermore National Laboratories). All these instruments are undergoing continuous improvement. Here we highlight some of the major developments in Year 6.

2.4.3.2.1. **Spectral Domain AO-OCT (Don Miller, Indiana University)**

One of the most exciting new instruments developed during Y6 has been the spectral-domain OCT system equipped with adaptive optics, developed by Don Miller and his group at Indiana University. The system layout is shown in Fig. 2.4.3.1.

The AO SD-OCT camera is based on a free-space parallel illumination architecture. Short bursts of narrow B-scans of the living retina can be acquired at 500 Hz during dynamic AO compensation (up to 14 Hz) that corrects the most significant ocular aberrations across a dilated 6 mm pupil. Images were also acquired of similar patches of retina with a commercial OCT (Stratus OCT3, Zeiss Meditec) and with a fiber-based scanning SD-OCT, which did not contain AO. Images from these established instruments were used to facilitate comparison with and validation of the AO-OCT instrument. Fig. 2.4.3.2 shows four AO SD-OCT images that were extracted from some of the best short burst videos on one subject. The images were acquired at two different retinal eccentricities (1 and 2.4 deg). The images from the three cameras contain grossly similar bright and dark bands that occur at similar depths in the retina. Interestingly, the stratification of the intra-retinal layers appears most defined in the AO-OCT images (left two columns) even though the AO-OCT images are somewhat darker, which suggests a reduced signal-to-noise. These and other results indicate the AO-OCT instrument is sufficiently sensitive to detect reflections from essentially all major layers of the retina (NFL to retinal pigment epithelium (RPE)).
Figure 2.4.3.1. (A) Concept layout shows the AO system as part of the OCT detection channel. (B) Detailed layout of the AO-OCT retina camera which consists of four sub-systems. (1) AO system corrects the ocular aberrations using a 788 nm SLD, Shack-Hartmann wavefront sensor, and Xinetics deformable mirror (short dashed line). (2) Pupil retro-illumination and fixation channels permit alignment of the subject’s eye to the retina camera. (3) Conventional flood-illumination is used to validate focusing in the retina (solid line). (4) Parallel SD-OCT acquires single shot B-scan images of the retina (long dashed line). Details of the camera are given in the text.

The 3D resolution of the B-scans (3.0x3.0x5.7 microns) is the highest reported to date in the living human eye and is sufficient to observe the interface between the inner and outer segments of individual photoreceptor cells, resolved in both lateral and axial dimensions.
Figure 2.4.3.2 (left two columns) B-scan images acquired with the AO parallel SD-OCT instrument in Fig. 2.4.1 with and without AO at 1 and 2.4 deg eccentricity (superior). (right two columns) Stratus OCT3 and scanning SD-OCT B-scans are shown at the same retinal eccentricities. All images were acquired on the same subject and are 100 microns wide and 560 microns deep. (bottom) The interface between the inner and outer segments and RPE are enlarged and displayed as amplitude on a linear scale (as opposed to a log scale). Minor thresholding was used to enhance contrast. (far right) Labels for retinal layers. Images without AO are normalized to the corresponding AO images, including the enlarged images. Depth of focus (dof) is displayed at the left.

2.4.3.2.2. Progress on the LLNL MEMS AO Phoropter

The MEMS AO Phoropter was designed and constructed by LLNL in collaboration with Bausch and Lomb, Boston Micromachines Corporation, Sandia National Laboratories, University of Rochester, and Wavefront Science Corporation. The device is intended to provide a rapid automatic measurement of the eye’s wave aberration from which a prescription for vision correction can be computed, avoiding the need for a conventional subjective refraction. The device is also equipped with a MEMS deformable mirror, allowing the patient to view the visual benefit of the particular prescription specified by the wavefront sensor. It is possible to measure visual performance, such as visual acuity, as in a conventional phoropter. The device currently resides at the University of Rochester, where Julianna Lin is now completing final testing. There have been a number of significant improvements at the University of Rochester, including the installation of two new upgrades of the Boston Micromachines deformable mirror. BMC’s new 3.5 micron stroke mirror with 140 actuators was installed in June. This mirror rivals the performance of Xinetics mirrors, is ~5 times less expensive and is only 4.8 mm on a side.
Closed loop tests performed using this mirror showed that the system was able to correct for static aberrations within 1-2 seconds. Closed loop tests on human eyes are currently underway at Rochester. Steve Jones at LLNL has also made numerous improvements to the software for the system. These include changes to the user interface, making it easier to use, and the addition of features to allow customization of the control loop algorithm. The phoropter will move to Bausch and Lomb for clinical studies in mid-summer 2005.

2.4.3.2.3. Measurements of fixational eye movements with the AOSLO

One of the unexpected outcomes of the vision science theme is that adaptive optics has provided vision science with new instrumentation to measure eye movements that is superior in resolution to any other technique. The figure below (Fig. 2.4.3.3) compares records of eye position computed from AOSLO high resolution images of the cone mosaic with those from a dual Purkinje image eye tracker, which is typical of highly accurate eye trackers in use today. The adaptive optics-based method is not subject to the artifacts of lens motion that characterize the dual Purkinje tracker.

![Figure 2.4.3.3. Eye movement records from AOSLO video and a dual Purkinje image eye tracker.](image)

2.4.3.2.4. Dewarped and Stabilized Video Streams for Adaptive Optics Scanning Laser Ophthalmoscopes

Adaptive optics scanning laser ophthalmoscopes have the advantage of providing video-rate imagery of the living retina with high axial and transverse resolution. However, one of the main factors corrupting image quality in these instruments is the natural motion of the eye not only between frames but also within frames. Motion between frames is easily dealt with by frame registration algorithms, but image dewarping within frames is more troublesome. The Montana group (C. Vogel, PI), following on the work at Houston described above, has developed an improved motion estimation algorithm and applied these motion estimates to dewarp images from AOSLO video streams. Fig. 2.4.3.4 shows an eye motion estimate obtained from the video stream of an AOSLO using the Montana algorithm.
The effects of dewarping cannot be readily seen in static images but may be seen in the stabilization videos whose web links are listed below:
http://www.math.montana.edu/~vogel/Vision/AviFiles/OC_foveal_PRs.avi
http://www.math.montana.edu/~vogel/Vision/AviFiles/OC_dewarp.avi

In addition, dewarped images were used to successfully de-noise images by co-adding registered dewarped frames. This project is an excellent example of CfAO investigators working in “Center mode.” The software under development, which emerged from a collaboration between vision scientists (Roorda, Stevenson) and a mathematician whose links were primarily with astronomy (Vogel) will be made available to ALL the vision research groups within the Center. This software sharing will improve the quality of the data in all CfAO laboratories through a coordinated effort on a significant problem. Future work will focus on the development of software that can dewarp retinal images in real-time, in addition to the off-line capability that has already been demonstrated.

2.4.3.3. AO system calibration and deconvolution of retinal images

Julian Christou (UCSC) has continued to help the vision nodes with AO system calibration. For example, he has visited Rochester to help researchers there compare wavefront sensor estimates of the PSF with measurements taken with the science camera. He is also helping to supervise Sapna Shroff at Rochester, not only in the deconvolution of retinal images but also in an effort to implement structured illumination in retinal imaging. The goal of the latter project is to nearly double the resolution of AO systems for retinal imaging beyond the diffraction cut-off. Christou has also visited Indiana University to address issues of calibration and deconvolution in their AO OCT system.
2.4.3.4. MEMS Deformable Mirror Development: Long Stroke MEMS Mirrors for Vision Science

The commercialization and accessibility of vision AO systems hinges on development of deformable mirrors that are smaller (<1 cm diameter), less expensive (<$1000), and have larger stroke (10-12 microns) than currently available mirrors. Since its inception, CfAO has been funding the development of MEMS mirrors to meet these specifications.

2.4.3.4.1. Boston Micromachines Corporation

Year 6 has proven to be a turning point in the CfAO’s MEMS mirror development efforts. In April, Boston Micromachines (Paul Bierdon, PI) delivered mirrors to Berkeley, Indiana University, LLNL, and Rochester with 3.5 microns of stroke. The mirrors have 140 actuators and are 4.8 mm on a side. These MEMS mirrors are comparable in performance to Xinetics mirrors, which have been the standard DM for vision science applications to date. Testing of these new MEMS mirrors is ongoing, but preliminary results are encouraging. This development is very important because the vision nodes in CfAO now have a source for mirrors for the new AO instruments under development. These instruments are being built with funding from two National Eye Institute Bioengineering Research Partnerships. Boston Micromachines has already begun feasibility work on a 6 micron stroke mirror, which it plans to deliver in Year 7.

2.4.3.4.2. Iris, AO MEMS Deformable Mirrors for Vision Science

Iris, AO continues to make progress toward its segmented MEMS mirrors for ophthalmic applications. In Year 6, Iris greatly reduced wafer-to-wafer variations in metal film adhesion by contracting metal seed layer deposition to a commercial vendor, Lance Goddard Associates. In partnership with Suss Microtec, Iris made the transition from solder bonding to gold thermocompression bonding for attaching mirror segments to actuator platforms. This transition has allowed them – for the first time – to release complete 37-segment deformable mirrors without bond failures. A complete released 37-segment array, bonded during the first assembly run at Süss Microtec is shown in Figure 2.4.3.5. Iris has measured more than 5 microns of stroke in a seven-segment sub-area of one such chip, which had 19 working segments total.

Figure 2.4.3.5 Left: Iris AO mirror interface board and deformable mirror chip with removable glass window. Right: Close-up view of released, fully assembled Iris AO 37-segment MEMS DM mounted in the board, with glass window removed.
Iris has taken delivery of one complete actuator-wafer lot manufactured to their specifications by Fairchild Semiconductor. Using facilities of the UC Berkeley Microlab as well as selected commercial vendors, they have demonstrated the ability to align photolithography tools in the Microlab to the Fairchild wafers, deposit and etch the bimorph and metal layers, and perform the polysilicon etch that defines the actuator platforms. Extensive testing on the Fairchild wafers, both as-delivered and after Iris AO post-processing, has shown pre-release yield to be high (> 80% die yield after post-processing). Although there is not yet enough comparable data to give meaningful post-release yield numbers, Iris has already been able to produce fully yielding released 37-segment actuator arrays (chips with no short- or open circuits or mechanical defects) – a very significant achievement from the first wafer lot. Devices produced so far have exhibited up to 8 microns of stroke and require drive voltages between 30 and 130V, depending on the specific design.

2.4.3.4.3. MEMX deformable mirror arrays

In the past year, MEMX (J. Koonmen, PI) has designed and tested three orthogonal approaches to MEMS deformable mirror arrays. All arrays function well, and provide sufficient vertical stroke to meet ophthalmic performance requirements. A summary of the key mechanical and electrical performance parameters of the MEMX arrays is provided below in Figure 2.4.3.6.

Mirror flatness is the last remaining hurdle for MEMX to overcome to fabricate a wavefront correction chip for ophthalmic adaptive optics. Significant improvements in mirror flatness were achieved recently. In particular, a robust and reliable process was developed which increased the flatness of fully reinforced (i.e., all 4 levels of polysilicon used in the mirror structure) MEMS mirrors from 250 mm ROC up to 1000 mm. ROCs in the 1000 mm range essentially eliminate any performance penalty resultant from the curvature of individual mirrors.

The results of a recent run have been encouraging. MEMX assessed the performance of 44 mirrors on each of 3 chips. All 44 mirrors are working well (100% yield) each with 93 pixel arrays. MEMX is achieving strokes of 10-11 microns at ~80 volts. Another key and very encouraging result is that MEMX has successfully demonstrated a metallization process with good results (i.e., flat mirrors) on a full-size array.

Figure 2.4.3.6. MEMX array parameters
2.4.3.4. Selectively Addressed MEMS Digital-Mirror Arrays

The BSAC group at Berkeley (R. Muller, PI) is working on a process that will produce MEMS deformable mirrors with the drive electronics integrated on the chip beneath each actuator. The project employs deposited polycrystalline silicon/germanium (poly-SiGe) to act as the mechanical layer. In Year 6 a complete fabrication process using poly-SiGe has been successfully developed to build MEMS-mirror carriages at temperatures compatible with foundry CMOS technologies. The group has established collaboration with Iris AO to assemble mirrors onto the poly-SiGe carriages. They are also designing the driving electronics using a foundry CMOS process on which the MEMS-mirror arrays will be built. The poly-SiGe mirror carriages are now being characterized and the test results will be described in research papers in preparation. Mastery of this process will provide the key to dense, high-performance digital-mirror arrays.

2.4.3.5. Scientific Achievements

This section enumerates some of the significant scientific achievements during Y6 that were enabled through CfAO funding for AO instrumentation. In each case, CfAO support was essential to create and maintain the adaptive optics technology required to undertake these experiments. In most cases, the experiments themselves were funded by sources other than CfAO, such as the National Eye Institute of NIH.

2.4.3.5.1. Microstimulation of the Cone Mosaic with Flash Location Recorded

During Year 6, the Rochester group (Joe Carroll) obtained IR images of the cone mosaic using adaptive optics. The resolution was only slightly less than that obtained with imaging with visible light (see the figure below). The advantage of IR imaging is that it allows unobtrusive retinal imaging at the same time as visual psychophysics is being done, as the imaging flash is not perceived by the subject. The Rochester Group also obtained images of the test flash and the retina at the same time (see the Figure 2.4.3.8 below), so it is possible to localize exactly where in the photoreceptor mosaic the flash hit. These data provide critical pilot data for mapping the color experience generated by stimulating particular photoreceptors. The goal of future work will be to identify specific retinal circuits through single cone stimulation.
2.4.3.5.2. Images of Primate Ganglion Cells Using the Fluorescence Adaptive Optics Scanning Laser Ophthalmoscope

A high magnification scanning laser ophthalmoscope was outfitted for fluorescent imaging of retinal cells. The system will incorporate adaptive optics, once AO control loop software has been developed. Preliminary in vivo images of primate ganglion cells (Bill Merigan and Dan Gray, Rochester) were taken with both a standard fundus camera and the high magnification SLO. See Figure 2.4.3.9. The narrow field images are the first ever taken of healthy ganglion cells at this resolution. Results were verified through histological comparison. For the remainder of Year 6, Rochester will develop and integrate adaptive optics into the fluorescent SLO. They will continue in vivo primate imaging and hope to obtain the first ever adaptive optics enhanced images of in vivo ganglion cells. Additional future projects with this instrument include attempts to achieve increase axial resolution in fluorescent imaging with two-photon ophthalmoscopy.
2.4.3.5.3. **Influence of neural factors on the aberration correction that optimizes subjective image quality.**

Experiments performed with the Rochester AO Ophthalmoscope (Li Chen in collaboration with Pablo Artal, University of Murcia, Spain) suggested that the eye is adapted to its particular pattern of higher order aberrations, because the subjective blur produced when viewing a scene through one’s own wave aberration was less than that when the wave aberration was rotated. In Year 6 the Rochester group studied whether this neural adaptation modifies the amount of aberration correction that produces the best subjective image quality. This may have important practical consequences for customized vision correction in eyes with large amounts of higher order aberrations.
Three subjects performed two tasks, method of adjustment and matching, while viewing a monochromatic stimulus through the Rochester Adaptive Optics System. In both tasks, the subject’s wave aberration was multiplied by a scaling factor between 1 and –1, where 1 corresponds to the normal wave aberration, 0 to aberrations minimized with adaptive optics, and –1 to the normal wave aberration but with the sign reversed. The visual stimulus was high-contrast, containing many sharp edges at all orientations. In the adjustment task, subjects adjusted the scaling factor to find the best subjective image quality. In the matching task, subjects adjusted the amount of defocus to match the blur corresponding to different factors multiplying the aberrations.

For the method of adjustment task, all observers chose a scaling factor significantly greater than zero, ranging from 0.03 to 0.18. This is consistent with a small amount of neural adaptation since the best image quality occurred when the wave aberrations were shifted slightly in the direction of the normal wave aberration. For the matching task, each of the three subjects’ data revealed a small amount of neural adaptation since the amount of defocus required to match subjective image quality was minimal for aberration factors slightly greater than zero. The best subjective image quality occurred when some aberrations are left uncorrected. Neural adaptation slightly modifies the best aberration correction, though this effect averaged only ~12% of complete adaptation and may well disappear following longer visual experience with fully corrected optics. The group reached the important conclusion that neural adaptation is neither large enough nor probably permanent enough to warrant partial instead of complete correction of the eye’s aberrations with customized contact lenses or refractive surgery.

2.4.3.5.4. Investigate the rapid fluctuation in the reflectance of single cones and its dependence on photopigment bleaching using a high-speed conventional flood-illumination AO retina camera.

Dynamic fluctuation in the reflectance of single cones has been reported to occur over periods of minutes to many hours in the living eye. The cause of these fluctuations is unknown, although a relationship to disc shedding has been suggested. However, the reflectance fluctuation has never been measured at short time scales on the order of seconds or less. The Indiana group (Don Miller, PI) monitored single cone reflectance over a period of a few seconds using the Indiana AO retina camera. For the purposes of imaging and bleaching cones, a 670 nm light source flood illuminated a 1.5 deg retinal patch at 1.4 deg ecc. The temporal coherence length of the 670 nm source was measured at 126 microns in tissue, assuming a refractive index of 1.43 for the tissue (e.g. photoreceptor outer segments). Cone images of 2 msec duration were acquired at 30 Hz over 4 sec intervals. The 30 Hz strobing light also acted as a bleaching source providing 84x10⁶ trolands and bleaching 98% of the cone photopigment after 2.3 sec. Fluctuations in the retinal reflectance were assessed at both the level of individual cones and across large patches containing many cones. As a representative example of the many videos collected under a variety of conditions, Fig. 2.4.3.10 shows the first frame of a registered stack of 120 images that were acquired in 4 seconds. Four hundred cones (12 of which are labeled in the figure) were selected and their intensities followed through the 120-image video. Fig. 2.4.3.11 shows the raw reflectance trace of several cones that were determined to have the highest and lowest RMS fluctuations of the 400.
Figure 2.4.3.10 First frame of a registered stack of 120 images that were acquired at 30 Hz using conventional flood illumination and dynamic AO (15 Hz). The field of view is 0.8 degrees and centered at 1.4 degree retinal eccentricity. Exposure duration was 2 msec. Labels (c1 to c12) point to individual cones, some of which oscillate rapidly during the 4 second video.

Figure 2.4.3.11. Raw intensity fluctuations of individual cones over the first 2.3 seconds of the 4 second video. Intensity profiles are shown for cones with the (left) highest and (right) lowest RMS intensity fluctuations out of the 400 selected.

A two-surface optical model that incorporates at least part of the reflected cone-guided light is found to show good agreement with at least the cones that highly fluctuate. Of the 400 cones studied, roughly one half showed evidence of a chirped oscillation as predicted by the theory. This project dovetails nicely with work underway in Roorda’s laboratory at UC Berkeley. The latter group has shown a significant reduction in speckle in AOSLO retinal images with the use of incoherent light in the point source instead of coherent light. It may be that much of this reduction is due to a reduction in the interference effects responsible for the temporal fluctuations observed by Miller’s group.

Fixation jitter, motion discrimination and retinal imaging
Recent advances in retinal imaging allow researchers to simultaneously stimulate and image the retina with a resolution on the order of one cone diameter. Scott Stevenson, Avesh Raghunandan, Jeremie Frazier, Siddharth Poonja and Austin Roorda (U. Houston) have exploited this capability to examine how fixational eye movements influence motion discrimination judgments. Specifically, the team examined up vs. down motion discrimination under referenced and unreferenced conditions, and imaged the retina with an Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO) so that the exact retinal position of the stimulus was
A single-interval, forced-choice psychophysical procedure was used to measure up/down discrimination thresholds for displacement of small, foveally viewed bar targets. Targets were 3 by 19 arc min dark bars on a bright background (referenced motion condition) or 5 by 40 arc min bright bars in an otherwise dark environment (unreferenced motion condition). AOSLO video sequences were recorded for off-line registration of retinal images. Psychometric functions and threshold determinations were then made for spatiotopic (bar motion in image) and retinotopic (bar motion on retina) frames of reference.

The team found that referenced motion thresholds were always better when expressed in a spatiotopic frame of reference, indicating that eye movements were compensated for in the judgments. Unreferenced motion showed the opposite relationship, with retinotopic judgments being generally more accurate than spatiotopic judgments, but subjects were still able to make some compensation for eye motion. The group concluded that subjects make precise judgments of displacement in spite of relatively large retinal image motions due to fixation jitter, as long as there is a frame of reference. Even without a frame of reference, subjects show some compensation for their eye movements, indicating that some source of extraretinal information about fixational jitter is available.

2.4.3.6. Partnerships and Commercialization

Participants in the Vision Theme are exploring relationships with companies in an effort to commercialize adaptive optics-related technology. We have established close contact with a number of companies including Bausch and Lomb, Carl Zeiss Meditec, Ciba Vision, Wavefront Sciences, Reichert, and Optos. In the next few months, Bausch and Lomb plans to test the MEMS AO Phoropter constructed by LLNL in collaboration with U Rochester, Wavefront Sciences, Boston Micromachines, and Sandia National Laboratories. They are also working closely with U. Rochester on the development of customized contact lenses. U. Rochester (Williams) and U. Houston (Roorda) have also formed a close relationship with Optos, a company in Scotland that produces an extremely wide field fundus camera. They plan to incorporate AO into their present instrument. A license agreement with Optos is nearly complete.

2.4.3.7. Vision Science Knowledge Transfer


The Center for Adaptive Optics is nearing the final stages of completing a manual that will contain basic and detailed information on how to design, build, calibrate and implement adaptive optics systems for vision science applications. The goal is to finish this project by the end of Year 6. The manual will be published in Year 7. Several CfAO members in the vision science and astronomical communities are contributing chapters for this book, which exemplifies the collaborative nature of CfAO. The editorial committee has seen rough drafts of all but two chapters. Most chapters are either in the technical and editorial review phase, or have undergone this process and are now being
molded into their final submission. In the summer of 2005, the editorial committee will meet once the final chapters have been submitted to synthesize all of the chapters into one publication. Then, the manual will be turned over to Wiley Interscience for indexing, formatting, and publication. Jason Porter (University of Rochester), Julianna Lin (University of Rochester), Hope Queener (University of Houston), Abdul Awwal (Lawrence Livermore), and Karen Thorne (formerly of Indiana University) are members of the editorial committee.
3. Education

3.1. Educational Objectives

The mission of the CfAO Education and Human Resources (EHR) program is to catalyze institutional and cultural changes that will broaden access to CfAO-related fields, utilizing the unique resources of the Center. A range of programs has been developed and implemented focusing on this mission. The impact of CfAO EHR activities is measured by success in each of four interwoven strategies:

- **TOOLS.** Implement activities and programs that broaden access to CfAO related fields.
- **PRACTICES.** Involve CfAO members in CfAO EHR programs and activities, and specifically in educational practices that broaden participation.
- **PARTNERSHIPS & LINKAGES.** Develop linkages and partnerships that broaden participation in the CfAO and CfAO sites.
- **PEOPLE.** Advance students that will broaden participation of the CfAO and CfAO fields.

3.2. Performance and Management Indicators

The CfAO measures short-term and long-term success by monitoring progress in the four major areas as follows:

**TOOLS.** Implement activities and programs that broaden access to CfAO related fields.
- Programs developed, implemented, and documented
- Activities (within programs or stand-alone) developed, implemented, and documented
- Courses developed, implemented, and documented
- Progress in sustaining programs, activities, and courses beyond CfAO Year 10
- Publication of new knowledge learned from programs, activities or courses
- New educational pathways stimulated by, or spun off of, programs, activities, or courses

**PRACTICES.** Involve members in CfAO EHR programs and activities, and specifically in educational practices that broaden participation.
- Number of CfAO members involved in CfAO EHR
- Number of CfAO members that incorporate new teaching or mentoring strategies into their practice
- Number of CfAO graduate students and postdocs who implement inquiry based teaching strategies
- Number of CfAO graduate students and postdocs who move into faculty positions, and incorporate inquiry based teaching strategies
- Number of new research proposals that include EHR components due to affiliations with CfAO
- Number of communications that include research and EHR
PARTNERSHIPS & LINKAGES. Develop linkages and partnerships that broaden participation in the CfAO and CfAO sites.
- Linkages between CfAO sites and organizations that serve significant numbers of students from underrepresented groups
- New pathways that broaden access to CfAO and CfAO related fields
- Joint activities, programs, and courses developed and implemented by CfAO and organizations that serve students from underrepresented groups
- New mechanisms for engaging relevant communities in the CfAO and CfAO related fields

PEOPLE. Broaden participation of CfAO and CfAO fields by advancing students from underrepresented groups.
- Number of underrepresented undergraduates participating in CfAO activities (research and education)
- Number of participating underrepresented undergraduates retained in Science, Technology, Engineering, and Mathematics (STEM) education or careers
- Number of underrepresented undergraduates advanced into CfAO, and CfAO related, graduate programs
- Number of underrepresented graduate students participating in CfAO activities (research and education)

3.3. Problems Encountered Reaching Education Goals
A continuing challenge faced by CfAO EHR has been the development of projects on the Big Island of Hawaii, where Mauna Kea and its associated observatories are located. Mauna Kea is extremely important to the astronomical community, but weak community support and lack of community involvement in the observatories has been an ongoing concern. Significant progress initiating new CfAO projects on the Big Island has been made in the last year. We are both encouraged and hopeful of having a positive impact on the Big Island’s indigenous community and their future involvement with the observatories.

3.4. The Center's Internal Educational Activities
3.4.1. Professional Development Workshop

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Annual Professional Development Workshop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter and Barry Kluger-Bell</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>CfAO graduate students and postdoctoral researchers; also some scientists and education partners</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>40</td>
</tr>
</tbody>
</table>

http://cfao.ucolick.org/EO/PDWorkshop/
Goals:
1) Develop inquiry-based teaching skills in CfAO and CfAO-related graduate students and postdoctoral researchers
2) Facilitate the incorporation of inquiry based teaching strategies in CfAO EHR programs
3) Develop partnerships and collaborations within the scientific, technical and educational community of Hawaii.
4) Build a community of practice amongst graduate students and postdoctoral researchers.

Project Description: The CfAO Professional Development Workshop is an annual event that brings together graduate students, postdoctoral researchers, and education partners for an intensive week of activities on teaching and learning science. Workshop participants compare hands-on approaches to teaching, engage their own personal inquiry experience, and participate on an inquiry design team. Participants also present their research to the Maui technical and educational community through the Maui High Tech Industry Education Exchange.

Participants may return to the workshop for multiple years to gain a deeper understanding of inquiry, and to take on leadership roles with direct mentoring by workshop staff. In 2004 these leadership roles were formalized and returning participants were matched in roles depending upon their past experiences and their interest in developing new skills. The roles are now formalized as follows: inquiry co-facilitator, inquiry shadower, discussion group leader, design team leader, and assessment activity leader. In addition, we include small working groups to tackle workshop challenges; in 2005 we included the “Connecting Theory and Practice (CTP) Working Group.” A detailed description of roles for returning participants is available at: http://cfao.ucolick.org/EO/PDWorkshop/roles.php.

Participation in the Professional Development Workshop on its own is generally a very beneficial experience. However, the follow-up teaching experience in one of CfAO’s “teaching labs” can be a transformative experience. We have developed many opportunities for workshop participants to pilot their new teaching skills, and then reflect on their experience with peers. The combination of the workshop and the teaching experience has led to the development of many new inquiry activities and a cadre of reflective science teachers with proficiency in inquiry based teaching approaches.
**Outcomes:** Immediate responses to the workshop are determined through a post-workshop survey. A complete summary of the findings is available in a report prepared by our external evaluator, Julie Shattuck and Associates, at [http://cfao.ucolick.org/EO/PDWorkshop/strategic.php](http://cfao.ucolick.org/EO/PDWorkshop/strategic.php). One of the most significant gains reported by participants was the pre/post shift in how they felt about their abilities to construct an inquiry activity. Before the Workshop, only 29% reported having “some” or “a great deal” of capacity to create an inquiry lesson. At the conclusion of the Workshop, this number rose to 87% (see Figure 3.2).

![Figure 3.2 Workshop participants’ pre/post ratings of their capacity to design an inquiry activity for a teaching situation](image)

After returning from the workshop, an increasing number of participants design new inquiry activities and/or teach an inquiry-based instructional activity. Workshop staff observe activities, review lesson plans, and debrief instructors to learn about how they incorporated inquiry into their activities. The following inquiry activities were all designed by teams of workshop participants and taught in 2004-2005:

- Variable star project and inquiry activity (Stars, Sight and Science)
- Galaxy Project (Stars, Sight and Science)
- Planetary Nebula Project
- Color, Light and Spectra (Mainland Internship Short Course)
- Color and Light, version 2 (Akamai Short Course)
- Color and Light (Hartnell Short Course)
- Color, Light and Spectra (Akamai Observatory Short Course)
- Table Top Optics (Stars, Sight and Science)
- Camera Obscura (Akamai Short Course)
- Lenses and Refraction (Akamai Short Course)
- Photodiode/detector Activity (Akamai Short Course)
- Physiology of the Eye (Rochester Saturday Open Lab)
- Color Vision Inquiry (Rochester Saturday Open Lab)
- Retinal Anatomy (“speed inquiry”)
- Research Practices session (Mainland Internship Short Course)
- Marine Ecology Inquiry (COSMOS, Marine Ecology Course)
3.4.2. Mini-Grant Project

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Mini-Grant Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>All CfAO graduate students and postdoctoral researchers</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>1-2 per year</td>
</tr>
</tbody>
</table>

http://cfao.ucolick.org/EO/Minigrants/index.php

**Goals:**

Mini-Grants are designed to increase the versatility of Center graduate students and postdoctoral researchers through exposure to and training in the diverse fields within the CfAO research and education programs.

**Project Description:** Mini-Grants facilitate exchanges of young researchers between vision science, astronomy and education. Graduate students and postdoctoral researchers are invited to submit one-page proposals outlining a visit to a CfAO site so as to gain experience in a different discipline: for example astronomers visiting vision science sites and vice versa.

3.5. The Center's External Educational Activities

3.5.1. Stars, Sight, and Science Program

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Stars, Sight, and Science Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
</tbody>
</table>
| Intended Audience | Primary audience: 8-10 graduate students and postdocs developing new teaching skills  
                     Secondary: 15-18 underrepresented high school students |
| Approx Number of Attendees (if appl.) | Graduate students & postdocs: (8-10)/year  
                     High school students: (15-18)/year |

**GOAL:**

*Stars, Sight, and Science* has two major goals: 1) Develop a learning environment where scientists have the opportunity to implement new, inquiry-based and problem-based teaching, mentoring, and assessment strategies; 2) Motivate participants to prepare themselves to pursue an STEM degree (2-year or 4-year) at college.

**Project Description:**

The four-week summer immersion experience includes three coordinated courses on vision science, astronomy, and science communication developed by CfAO:

- Astronomy Today: Observing the Universe
- Human Vision: Photons, Proteins, and Perception
- Transferable Skills
This program is offered in conjunction with the California State Summer School for Mathematics and Science (COSMOS) program at UCSC. Beginning in Year 5, the COSMOS program has agreed to cover the majority of costs for Stars, Sight and Science, indicating the institutional commitment to this successful program. The CfAO now covers a small percentage of CfAO staff time and the costs associated with bringing in instructors from remote CfAO sites.

Stars, Sight, and Science focuses on middle to high achieving underrepresented students, providing them with interdisciplinary, inquiry based experiences, and small group projects led by graduate student advisors. The instructional team includes lead instructors, project advisors, guest instructors, and a high school science teacher. The program uses adaptive optics as a starting point to foster an interest in related fields, such as vision science, astronomy, engineering, and advanced instrumentation.

The Stars, Sight and Science program is one of CfAO’s “teaching labs.” All instructors and most project advisors attend the Professional Development Workshop to learn about inquiry-based teaching and develop their own inquiry activities. The instructional team has incorporated inquiry into laboratory activities and projects that have a basis in both vision science and astronomy.

Outcomes:

The Stars, Sight and Science program has become an extremely valuable teaching laboratory for CfAO graduate students and postdocs. Through the program, we have developed and taught a range of new inquiry-based instructional materials.

Fig. 3.3 Stars, Sight, and Science COSMOS students visiting Professor Austin Roorda’s lab during a field trip to the UC Berkeley School of Optometry.

21 Underrepresented minorities defined here as Hispanic, African American, Native American, Pacific Islander.
3.5.1.1. Inquiry design and practice in Stars, Sight and Science

To illustrate the integration of inquiry into Stars, Sight and Science, two activities are described below: 1) Galaxy Project and 2) Table Top Optics.

3.5.1.1.1. Galaxy Project

This project utilizes elements of inquiry to teach students about galaxies, and has been reported on by graduate student Scott Seagroves. Through an inquiry activity, students learn about the color and shape of galaxies. This inquiry starts with students looking at a set of high-resolution images of galaxies spanning different morphology and environment. As they study the images they are encouraged to raise “I notice” or “I wonder” type questions. Students came up with questions like “the top galaxy is like the bottom one, except that it has that yellow part coming off. Why?” or “Why are some very blue and some very red or yellow?” or “Why do some look like they are rotating, like a tornado?” or “Maybe a bigger galaxy sucked in a smaller one?”

As the investigative portion of the project progressed, students developed their own galaxy classification scheme to organize what they were observing. They read texts and web pages looking for basic facts about galaxy components and terminology. At the appropriate moment, the Hubble classification system was introduced by the instructors and compared with those the students had developed. Throughout the process there were mini-lectures, synthesis, dialog and re-questioning. In this activity, students experienced discovery by assembling components of “knowns” rather than determining the fundamentals by first hand investigations, as one might with topics such as basic optics.

The Galaxy Project has opened up new lines of thinking within the CfAO as to how inquiry can be applied to astronomy teaching. In 2004, the “Planetary Nebula Project”, with consultation from the Galaxy Project team, was modeled after it.

3.5.1.1.2. Table Top Optics Inquiry

This inquiry was designed in 2001 and has been used each year since, with new inquiry facilitators rotated in to gain experience in the tools and strategies for teaching with inquiry. An excerpted description of the Lynne Rashke’s Table Top Optics Inquiry appears in Box 1.
BOX 1: Excerpt from Lynne Raschke’s Activity Documentation of Table Top Optics

**Content Goals:** Our students’ prior knowledge of optics varied dramatically. Some of our students had no exposure to topics in optics while others had a significant introduction to it in physics classes. Because of this wide variety in background knowledge, we found it helpful to create a tiered set of content objectives. It was our hope that all students would understand the content at the first tier, many students would grasp the second tier content material, and a few of the more advanced students would understand the material at the highest tier.

- Our first tier content objectives consisted of understanding: the way lenses and mirrors bend the path of light; the difference between diverging and converging beams of light; and the different way convex and concave optical elements affect beams of light.
- Our second tier content objectives consisted of understanding: the concept of focal point; the way a convex lens forms images (including the process of image inversion); and the relationship between magnification and the distance to the image plane.
- Our third and final tier content objectives consisted of understanding: the relationship between the curvature of the lens and the focal point; the derivation of the law of reflection; and the phenomenon of total internal reflection.

**Process Goals:** Our process objectives were based on the skills we hoped our students would learn and utilize during the rest of COSMOS. They included: the ability to be self-motivated in exploring phenomena; the ability to generate questions; the ability to generate hypotheses and test them; and the ability to communicate clearly through presentations to their peers.

**Activity:**
- Inquiry Starters: Students rotate through four different stations spending 20 minutes at each station exploring optical phenomena, and generating questions
- Question Sorting: While students take a break, instructors sort questions into major areas that will naturally lead into investigations related to the content goals. A few sample questions from a couple of themes are:
  - Bending Light: Why when you put both the convex and concave glass pieces together does the light come out as if it was never changed?
  - Laser Light Path: Why is the light bent when aimed through the prism?
  - Image Size: How come when you use a fat lens and a thin lens you get a huge F?
  - Focusing Images: Why does the image disappear when you put two same lenses in front of each other?
- Focused investigations: students form small teams and carry out their own investigations to answer their own question
- Presentation and synthesis: All investigation teams present the results of their investigations. One of the inquiry facilitators ties all the investigations together, validating the contributions of each team, clarifying any unresolved issues, and summarizing the content goals.
3.5.1.1.3. Dissemination:
A publication\textsuperscript{22}, describing the overall COSMOS program includes a special 2-page section on CfAO entitled: “A special partnership: CfAO Stars, Sight, and Science.”

3.6. Summary of Professional Development Activities for Center Students

1. Annual Professional Development Workshop – The workshop builds teaching, collaborative teamwork, communication, and other important skills.
2. Mini-Grant Project - This project develops cross-disciplinary collaborative skills, as well as providing students with a broadened professional network and direct experience in a new working environment.
3. Summer School on Adaptive Optics – Courses are intended to convey the scope and application of adaptive optics to research. This is a professional development course for both astronomers and vision scientists. See description in Knowledge Transfer section of this Annual Report.
4. Center retreats and workshops – Center students have multiple opportunities each year to participate in Center retreats and workshops, with many opportunities for presenting their research. Our industry affiliates program meets at our retreats and is an excellent venue for students to make contacts in industry.

3.7. Mainland Internship Program

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Four Year and Community College Internships</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Undergraduates, primarily from underrepresented groups, with an emphasis on community college students</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>10-15 each year</td>
</tr>
</tbody>
</table>

Web link: http://cfao.ucolick.org/EO/internshipsnew/mainland/

The Mainland Internship program provides research experiences for community college and 4-year university students, with an emphasis on students from underrepresented groups. Students are placed at CfAO sites and work intensively on an authentic research project under the guidance of a CfAO advisor (faculty member or senior scientist) and supervisor (often a graduate student or postdoc). Interns are integrated into the research team, gaining an in-depth knowledge of the research subject, as well as professional skills and an expanded network. Throughout the internship, communication is an ongoing theme. At the end of the summer, interns give a ten-minute formal oral presentation. For many students this is their first experience in presenting at this level, so we have implemented a set of activities that give students all the resources they need to deliver a

\textsuperscript{22} C. Moran, J. Roa, B.K. Goza, and C.R.Cooper, Success by Design: Creating College-Bound Communities (UC Santa Cruz EPC, Santa Cruz, CA), pp. 85-100.
high quality, professional presentation. Our survey of past interns indicates that the preparation and delivery of the oral presentation is one of the most valuable elements of the program.

A unique element of the Mainland Internship Program is our five-day short course that precedes the research experience. The goal of this course is to establish a community among the students; prepare them for the research environment; orient them to the CfAO; and teach them some of the background necessary for a successful experience in the multi-disciplinary environment of CfAO. The short course prepares students for their coming research experience through a set of inquiry activities, laboratories, lectures, discussions, and small team problem solving. Topics include astronomy, vision science, engineering, research practices, and preparation for graduate school. The short course was developed by CfAO graduate students and has now become a model for three other short courses. The Mainland Short Course is one of CfAO’s “teaching labs,” providing opportunities for piloting new inquiry based teaching activities.

Fig. 3.4 Mainland Interns using spectrographs during the “Color, Light and Spectra” inquiry.

### 3.7.1. Outcomes:

#### 3.7.1.1. Summary of accomplishments"

- At least 86% (37 of 43) of interns in the program are on track, remaining enrolled in a STEM program of study or entering the STEM workforce
- **4 interns have now entered STEM graduate programs,** and 2 of these are from underrepresented minority groups
- **6 interns will enter STEM graduate programs in 2005,** and 4 of these are from underrepresented minority groups
- The Hartnell Astronomy Short Course taught in 2004 was a successful recruitment tool, with 2 students from the course accepted into the 2005 Mainland Internship Program. Hartnell has awarded the CfAO the **Hartnell President’s Partnership Award.**
• Our partnership with the Hispanic Association of Colleges and Universities (HACU) awarded the CfAO an additional $25,000 in 2004 and 2005 for student support. HACU recruited 5 of the 9 students in the 2005 Mainland Program.

3.7.2. Mainland Internship Program Goals

GOAL #1: To retain and advance college students from underrepresented and/or underserved groups in STEM, by enhancing their skills, resources and confidence in CfAO related fields.

Students in the Mainland Internship Program are tracked over their career through emails and surveys that go out at least twice per year. A successful outcome is graduation with a Bachelor’s degree and then either graduate school or workforce entry. Workforce entry includes any position in science, engineering or technology, including science or math education.

Table 3.1 shows the status of the 43 interns who completed the program between 2002-2004. At this time, 25 students are currently enrolled in a STEM program (we believe this number is actually 28, but are unable to confirm the status of 3 students). Eleven students have graduated with degrees in a STEM area. Our current STEM retention rate (those still on track as undergraduates, graduate students, or in the workforce) is in the range of 86-93%, depending on the status of the 3 students who have not yet responded. It should be noted that this retention rate is not a final retention rate, as students are still enrolled, some at the community college level. Our goal is for 75% of our students to complete Bachelor’s degrees and be retained in STEM.

3.7.2.1. Mainland Intern Graduate School Entry

The CfAO has aimed to increase the diversity of Center graduate students, and has found this to be an extremely challenging goal. Since the Center’s commencement in 1999, we have had only one graduate student from an underrepresented minority group. However, the student was not significantly involved in Center activities, such as retreats, workshop, or the Professional Development Workshop and did not complete a doctoral program, as had been the intention, leaving with a Master’s degree.

The Mainland Internship Program provides a pool of prospective students for our graduate programs, and reflects our “grow your own” strategy. During the selection process, special attention is given to those students who have the academic qualifications and interests to enter graduate school. After running the program for several years, and a great deal of mentoring and advising, we are now seeing the Mainland Interns begin to enter graduate school. We now have five students in graduate school, two who are underrepresented minorities and two women:

- Donald Cox, UC Santa Barbara, Computer and Electrical Engineering, entered Fall 2003
- Kerry Highbarger, Optical Engineering, Ohio State, entered Fall 2004
- Amanda Young, Virginia Tech, Aerospace?, entered Fall 2004
• Bautista Fernandez, UC Santa Cruz, Electrical Engineering Master’s program, entered Fall 2004
• Yan Mei Wu, status unknown, last contact indicated she was applying.

In addition we know of 3 students who will be graduating this June, and all 3 have been accepted into graduate programs. Six Mainland Interns entered the workforce after graduating, and three of these have been accepted into graduate programs, bringing the total to 6 Mainland Interns entering graduate school in Fall 2005, 4 of which are from underrepresented minority groups. We know of one other student who will graduate and believe has been accepted into a graduate program, and two others we believe applied. However, we are unable to confirm the status of all three at the time of this report. The students who have been accepted are:
• Oscar Azucena, UC Santa Cruz, Electrical Engineering, Cota-Robles Fellow
• Carlos Andres Cabrera, UC Santa Cruz, Electrical Engineering
• Monica Pinon, UC Berkeley, School of Optometry
• Maribel Huerta, University of Houston, School of Optometry
• Meghan Brennan, Teaching Credential program
• Jennifer Holt

Table 3.1: Status of Mainland Interns as of 4/30/05

<table>
<thead>
<tr>
<th></th>
<th>Number (Percentage)</th>
<th>A. Enrolled undergrad in STEM</th>
<th>B. Left college w/o degree</th>
<th>C. Switched to non-STEM</th>
<th>D. Eligible to apply to grad school</th>
<th>E. Accepted to grad school</th>
<th>G. BA/BS earned</th>
<th>H. In grad school in STEM</th>
<th>I. Entered STEM workforce</th>
<th>J. Accepted to grad school</th>
<th>L. On STEM path*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>16 (37%)</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>13-15(81-94%)</td>
</tr>
<tr>
<td>Women</td>
<td>27 (63%)</td>
<td>16</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>21-23(81-85%)</td>
</tr>
<tr>
<td>Under-rep minority</td>
<td>28 (67%)</td>
<td>18</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>23-26(82-93%)</td>
</tr>
<tr>
<td>Other ethnicity</td>
<td>15 (33%)</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>12-13(80-87%)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>43</td>
<td>25</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>11</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>37-40(86-93%)</td>
</tr>
</tbody>
</table>

Under-rep group (women or minority) Not under-rep

**Men**

- **Women**

- **Under-rep minority**

- **Other ethnicity**

- **TOTAL**

* A + H + I. Range gives “confirmed” to “probable”
**GOAL #2:** To develop linkages and partnerships that will broaden participation in CfAO related fields.

Partnerships have been established with the following organizations:

**Hartnell College, Salinas, California**
(see section 3.4 below, “Hartnell Astronomy Short Course”)

**Hispanic Association of Colleges and Universities (HACU)**
HACU provided full financial support, including administrative costs for a total of $8,000 each, for 3 Mainland interns in 2004. They also assisted in student recruitment. The same very successful arrangement has been established for 2005.

**GOAL #3:** To incorporate inquiry-based teaching into CfAO related fields, by providing a “teaching lab” for newly trained instructors to gain experience and pilot instructional material.

The Mainland Short Course was taught by 5 CfAO graduate students and postdoctoral researchers in 2004. All five attended the CfAO Professional Development Workshop to prepare for inquiry-based teaching. The following inquiry-based activities were integrated into the Mainland Short Course:

- **Color, Light and Spectra Inquiry**
  Facilitated by Lynne Raschke (UCSC), Shelley Wright (UCLA), Adam Burgasser (UCLA), Julianna Lin (Rochester), and Seth Pantenelli (Rochester)

- **Lenslet Activity**
  Facilitated by Julianna Lin (Rochester), Kerry Highbarger (UCD), and Joy Martin (Houston)

- **Retinal Anatomy Inquiry**
  Facilitated by Julianna Lin (Rochester), Joy Martin (Houston), and Seth Pantenelli (Rochester)

- **Data Interpretation Activity**
  Facilitated by Lynne Raschke (UCSC), Shelley Wright (UCLA), Adam Burgasser (UCLA), and Julianna Lin (Rochester)

The Color, Light and Spectra Inquiry was also taught in the Astronomy Short Course, where Anne Metevier, Mark Ammons, and Jennifer Lotz all gained an experience in facilitating inquiry activities.

### 3.8. Akamai Internship Program

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Four Year and Community College Internships</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Undergraduates, primarily from underrepresented groups, with an emphasis on community college students</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>~12 per year</td>
</tr>
</tbody>
</table>

**Web link:** http://cfao.ucolick.org/EO/internshipsnew/akamai/index.php
The CfAO Akamai Internship is the outcome of a long-term investment in CfAO Hawaii partnerships. The internship brings together stakeholders from the Maui and Big Island communities with the common goal of increasing the participation of Hawaiians in CfAO related science and technology, and increasing the capacity of Maui Community College (MCC) to incorporate adaptive optics related technology into academic program offerings.

In 2004, the Akamai Program expanded onto the Big Island, with the new Akamai Observatory Short Course (see Section below) and several new internship positions. In Years 7-8, we will refine our Big Island component, based on results from our Summer 2005 efforts.

### 3.8.1. Akamai Optics Short Course

Akamai Interns are prepared for their research experience through the CfAO Optics Short Course on Maui, a 5-day intensive modeled after the Mainland Internship Short Course. This course is taught by CfAO graduate students and postdocs, and a Maui Community College (MCC) faculty member. The Short Course gives students a general background in optics and scientific processes through a set of inquiry based activities supplemented by lectures. In addition, internship hosts give a short talk on their work and what their assigned intern will doing for a research project. Akamai interns receive credit for the Short Course through MCC. Also see: http://cfao.ucolick.org/OE/internshipsnew/shortcourses/mauisc.php.

#### 3.8.1.1. Research Experience

The Akamai Interns are placed at high tech industry sites (primarily the federal contractors for the Air Force) and astronomical observatories. The following organizations hosted interns in 2003-2004 and will be encouraged to participate again in future years:

- Boeing
- Trex
- Akimeka
- Oceanit
- Maui High Performance Computing Center (MHPCC)
- W. M. Keck Observatory (Big Island)
- Smithsonian (Big Island)
- Textron
- Northrop Grumman
- General Dynamics

Akamai interns present their summer research at an AMOS Student Session held within the AMOS Technical Conference on Maui each September. The AMOS Student Session began in 2003 as a collaboration between CfAO, the Maui Economic Development Board, and the Air Force Maui Optical and Supercomputing Site (AMOS). This session fosters collaboration between the technical and educational communities of Maui, and provides students with an opportunity to experience a professional conference. Family
and other community members are invited to attend the student symposium, and we anticipate that this community participation will be better informed on technology issues and supportive of technologies in use on Haleakala.

3.8.1.2. Outcomes:

Summary of accomplishments:
- At least 55% (10 of 18) of the interns are working in technical positions, 4 part-time and still enrolled in a technical major in college; 6 working full-time.
- Akamai interns are working at the following Maui organizations: Oceanit, Textron, MHPCC, H&C, Oceanic Cable, and USGS.
- 3 students have now transferred to 4-year institutions
- 2 students who are working in technical positions are applying to graduate school for the fall.
- **The CfAO and Maui Community College were awarded $40,000** to develop a new astronomy course with AO components.
- The CfAO educational partnership with Maui has stimulated a new research collaboration, “Turbulence Simulator for Adaptive Optics,” involving Oceanit, the Maui Scientific Research Center, and the Laboratory for Adaptive Optics.

3.8.2. Akamai Internship Goals

GOAL #1: To retain and advance college students from underrepresented and/or underserved groups in STEM, by enhancing their skills, resources and confidence in CfAO related fields.

To date, **18 students have completed the program**, and 10 are currently working in technical positions (either full-time (6) or part-time and still enrolled (3). Two students who are working in technical positions are applying to graduate school for fall 2006.

### Table 3.2 Status of Akamai Maui Interns, as of 4/30/05

<table>
<thead>
<tr>
<th></th>
<th>#%</th>
<th>Men</th>
<th>13</th>
<th>72%</th>
<th>3</th>
<th>3</th>
<th>2</th>
<th>2</th>
<th>3</th>
<th>0</th>
<th>1</th>
<th>4</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Women</td>
<td>5</td>
<td>28%</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>A. Enrolled in Comm. College</td>
<td></td>
<td>Underrep minority</td>
<td>10</td>
<td>56%</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0</td>
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<tr>
<td>B. Received AA/AS</td>
<td></td>
<td>Other ethnicity</td>
<td>8</td>
<td>44%</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>2</td>
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<tr>
<td>C. Work PT &amp; enrolled</td>
<td></td>
<td>total</td>
<td>18</td>
<td></td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>D. Transfer to four year institution</td>
<td></td>
<td>Underrep group (Women or minority)</td>
<td>13</td>
<td>72%</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
GOAL #2: To develop linkages and partnerships that will broaden participation in CfAO related fields.

The following partners have been established:

**Maui Economic Development Board**
The Maui Economic Development Board collaborates on all aspects of the Akamai Maui Internship. They liaise with industry hosts, and are invaluable as our local program arm. Leslie Wilkins serves on the advisory committee, and is involved in all design and decision-making.

**Maui Community College**
Maui Community College (MCC) is involved in all aspects of the Akamai Maui Internship. Mark Hoffman (ECET), John Pye (astronomy), Wallette Pellegrino (Cooperative Education) are on the program advisory committee and are directly involved in all decisions, including program design, student recruitment and selection, coordination with industry hosts, and program completion. In addition the program has benefited from the strong support of Chancellor Clyde Sakamoto and Dean Suzette Robinson. MCC offers credit for the Akamai Optics Short Course through the Electronics and Computer Engineering Technology program.

**Air Force Maui Optical and Supercomputing Site**
The Air Force Maui Optical and Supercomputing Site (AMOS) provides crucial local support, encouraging federal contractors to participate in the program. AMOS provides facility tours during the short course, and beginning in 2003 supported a new Student Session at their annual AMOS Technical Conference. Each year 4-6 Akamai interns make presentations at the conference.

**New Activities with Maui Partners:**
1. **DEVELOPMENT OF A NEW ASTRONOMY LAB COURSE (JOHN PYE).**
   MCC, MEDB and the CfAO were awarded a $40,495 grant from the Center for Biophotonics (via NSF funds). This grant will fund the development of a new astronomy lab course at MCC. John Pye is the MCC Principal Investigator and will be working with Mark Hoffman on an adaptive optics course component.

2. **NEW ADAPTIVE OPTICS HARDWARE AND CURRICULUM (MARK HOFFMAN).**
   Mark Hoffman from MCC is leading an effort to build an adaptive optics demonstrator with associated software, including image post processing. This will be used in the new astronomy lab course, the Akamai Short Course, and eventually a new electronics course currently in the planning stage. The demonstrator will be on long-term loan to MCC, with the intent of permanent transfer to MCC in a year or so (once it is established as useful and integrated into MCC programs). Hoffman is leading a team that includes a UCSC graduate student, (who has already built a system like this), and several MCC students (from electronics and high performance computing studies).
3. AKAMAI CLUB HOSTS FIRST EVENT, 1/28/05: PRESENTATIONS, KAAIKE TOUR, AND TRIP TO HALEAKALA (MCC, MEDB, AMOS, CfAO).
Mark Hoffman is the faculty advisor for the new Akamai Club, which promotes education in both AO hardware and image post processing software for high performance computing.

As a mechanism for building interest in the Akamai program, MCC, MEDB, and AMOS hosted a day that included:
-- student presentations from past Akamai interns
-- CfAO staff internship presentation
-- tour of Kaaike facilities for visiting UH Manoa students
-- tour of the AMOS facilities led by Joseph Janni

A total of 14 MCC students and 9 UH Manoa students attended this event and went to the summit. It was an excellent recruitment mechanism, bringing in 6 applications, all of whom have been accepted into the program.

**GOAL #3:** To incorporate inquiry-based teaching into CfAO related fields, by providing “teaching lab” for newly trained instructors gain experience and pilot instructional material.

Led by Andy Sheinis (Postdoc, UCSC), the Akamai Optics Short Course uses a range of inquiry-based teaching activities, and has provided a number of graduate students and postdocs with teaching opportunities. The following inquiry activities were incorporated into the 2004 course, and were facilitated by Andy Sheinis, Sarah Martell (UCSC graduate student), Oscar Azucena (UCSC Post-bac Fellow), Mike Kuhlen (UCSC graduate student), and Mark Hoffman (MCC, faculty member):
- Color, Light and Spectra Inquiry
- Camera Obscura
- Lenses
- Photodiode/Detector Activity

The Akamai Optics Short Course has served as a very productive curriculum piloting project. A new instructional module teaching the fundamentals of color and light was piloted in the short course and has now been integrated into the regular MCC physics course. Each November several CfAO members assist in teaching this inquiry based unit, providing formal classroom teaching experience to the CfAO members, and enhanced teaching capabilities for MCC.

MCC is now building an adaptive optics system for educational use, along with accompanying instructional material, to be piloted this year in the short course.

### 3.8.3. Hawaii Island Akamai Observatory Program

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Hawaii Island Akamai Observatory Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Akamai Observatory Short Course: Claire Max</td>
</tr>
</tbody>
</table>
The CfAO is piloting the **Hawaii Island Akamai Observatory Program** in 2005, through a partnership with several Mauna Kea observatories, UH Hilo, and the Institute for Astronomy. A new part-time Internship Coordinator, Sarah Anderson, was hired with the support of the CfAO and Keck. Anderson assists with student recruitment, finding and briefing intern advisors, coordinating the short course, and many other logistical details that have been essential in implementing a program on the Big Island.

The program is based on the Akamai Maui Program and will include the Akamai Observatory Short Course, and apprenticeships at Mauna Kea observatories. A student symposium took place at the end of July at UH Hilo. Ten students have been accepted: 3 from UH Hilo; 5 from UH Manoa; 1 from Hawaii Community College; and one Hawaii resident enrolled at a mainland university. Information on the program can be found at: [http://cfao.ucolick.org/EO/internshipsnew/bigislandintern.php](http://cfao.ucolick.org/EO/internshipsnew/bigislandintern.php).

The Akamai Observatory Short Course is a sub-component of this effort and is led by Claire Max.

### 3.8.3.1. Program Implementation

The following activities were implemented in 2004 and the first part of 2005, which helped to bring the program to fruition:


- **The CfAO supported three undergraduate interns in the summer of 2004.** Students did not participate in a formal program, but were able to join in on some of the other CfAO internship program activities held for Maui or Mainland students.

- **Three Big Island Interns present at the CfAO Mainland Student Symposium** held in Santa Cruz on August 9, 2004.

- **Forum for Observatory and Technical Education**, December 14, 2004. Organized by Sarah Anderson and Gary Fujihara (Institute for Astronomy, University of Hawaii), this forum brought together members of the community to share information about existing and needed programs.

**Participants** Sarah Anderson Eng. Assistant W.M. Keck Observatory Liz Barton Director HIEDB Mark Chun IFA OA Engineer IFA Robert Fox Dept Chair UHH Physics and Astronomy Gary Fujihara Science Education & Public Outreach Institute for Astronomy Eric Hagiwara Teacher Waiakea High School- Academy of Math and Science Marlene Hapai Director MKAEC Paula Helfrich HIEDB Lisa Hunter Ass. Director Education & Human Resources CfAO Cathy Ishida Public
• **Presentation at the NSF:** Opening Doors in Hawaii: Astronomy Internships that Advance Students and Build Partnerships. January 26, 2005. Attended by approximately 20 NSF and AFOSR representatives.

• **Meetings with observatory directors and other personnel.** Throughout the year meetings have been arranged and follow-up emails sent to establish the program. We have met with directors from the Keck, Gemini, Subaru, and Canada France Hawaii Observatories.

• **CfAO – UH Hilo Internship Forum.** Held on February 1, 2005 at UHH, three interns from 2004 presented their projects with Chancellor Rose Tseng giving the opening comments and Robert Fox, Chair of Physics and Astronomy, the concluding remarks.

• **Table 3.3  2005 Hawaii Island Akamai Observatory Interns**

<table>
<thead>
<tr>
<th>Gender</th>
<th>Ethnicity</th>
<th>URM</th>
<th>UREP</th>
<th>School</th>
<th>Intern Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>White</td>
<td>0</td>
<td>0</td>
<td>UH Hilo</td>
<td>Keck</td>
</tr>
<tr>
<td>m</td>
<td>Pacific Islander</td>
<td>1</td>
<td>1</td>
<td>UH Manoa</td>
<td>Keck</td>
</tr>
<tr>
<td>m</td>
<td>White</td>
<td>0</td>
<td>0</td>
<td>Hawaii Community College</td>
<td>Keck</td>
</tr>
<tr>
<td>m</td>
<td>White</td>
<td>0</td>
<td>0</td>
<td>UH Manoa</td>
<td>Keck</td>
</tr>
<tr>
<td>f</td>
<td>Filipino</td>
<td>1</td>
<td>1</td>
<td>UH Manoa</td>
<td>SMA</td>
</tr>
<tr>
<td>f</td>
<td>White</td>
<td>0</td>
<td>1</td>
<td>UH Hilo</td>
<td>SMA</td>
</tr>
<tr>
<td>m</td>
<td>Native Hawaiian</td>
<td>1</td>
<td>1</td>
<td>UH Hilo</td>
<td>Gemini</td>
</tr>
<tr>
<td>m</td>
<td>White</td>
<td>0</td>
<td>0</td>
<td>UH Hilo</td>
<td>Gemini</td>
</tr>
<tr>
<td>m</td>
<td>White</td>
<td>0</td>
<td>0</td>
<td>UH Manoa</td>
<td>IFA</td>
</tr>
<tr>
<td>f</td>
<td>Asian Am</td>
<td>0</td>
<td>1</td>
<td>UH Manoa</td>
<td>Subaru</td>
</tr>
<tr>
<td>m</td>
<td>Asian Am</td>
<td>0</td>
<td>0</td>
<td>California Lutheran University</td>
<td>Subaru</td>
</tr>
</tbody>
</table>

3.9. **Mainland Courses**

3.9.1. **Hartnell Astronomy Short Course**

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Hartnell Astronomy Short Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Anne Metevier &amp; Lisa HUnter</td>
</tr>
</tbody>
</table>
**Intended Audience**

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Ed 286</th>
</tr>
</thead>
</table>

Community college students and high school seniors

Approx Number of Attendees (if appl.)

15-20 annually


A new **Astronomy Short Course** was developed and taught at Hartnell College, a minority serving community college near Santa Cruz CA, in June 2004, which was aimed at entering and enrolled community college students. Anne Metevier was the lead on this project, and received an NSF Postdoctoral Fellowship that includes her participation in the short course. Anne was assisted in teaching this five-day intensive course by a team of instructors, including Andy Newton (Hartnell Planetarium Director), Mark Ammons (UCSC graduate student), Jennifer Lotz (UCSC Postdoc), and a handful of others who assisted with selected activities. Metevier attended two CfAO Professional Development Workshops, and used the experience to incorporate inquiry-based teaching into the short course in a variety of ways. These included making use of many of the previously designed CfAO instructional material (some developed by Metevier) as well as developing new activities.

The Color, Light and Spectra Inquiry was taught in the Astronomy Short Course. It was facilitated by Anne Metevier (lead), Mark Ammons, and Jennifer Lotz who all attended the 2004 Professional Development Workshop. Ammons and Lotz were able to further develop their newly acquired teaching techniques during this inquiry.

Students in the Astronomy Short Course receive 1 unit through the Physics Department. Details on the 2005 Astronomy Short Course can be found at: [http://cfao.ucolick.org/EO/internshipsnew/shortcourses/hartnellastronomy.php](http://cfao.ucolick.org/EO/internshipsnew/shortcourses/hartnellastronomy.php).

One of the primary goals for the short course is to recruit Hartnell students for the CfAO intern program, and establish a long-term pathway between Hartnell and UCSC. A total of 19 students completed the course, and of the 19, four applied for the 2005 CfAO internship. **Two have been accepted and two others are on the waiting list**, which we feel is a very successful outcome.

Hartnell College has awarded the **Hartnell President’s Partnership Award to CfAO**, and an award ceremony was held at the CfAO on May 13, 2005.

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**3.9.2. Education 286: Research and Practice in Teaching and Learning Science**
<table>
<thead>
<tr>
<th>Led by</th>
<th>Doris Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intended Audience</td>
<td>Science and engineering graduate students</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>10-20 annually</td>
</tr>
</tbody>
</table>

Education 286 is a graduate level course at UCSC specifically designed for scientists and engineers who want to explore science inquiry teaching and learning. The course is taught by Doris Ash (Assistant Professor of Education) and offered at UCSC. However, students from other campuses may audit the course and attend via the CfAO’s videoconferencing facility. The course focuses on undergraduate and graduate level teaching but is applicable for those teaching at the high school level, or in an informal environment, such as museums. The course has three major elements: 1) research on best teaching practice in small and large groups; 2) learning and what research tells us about learners; and 3) how both of these relate to science inquiry. Students design and put into practice several teaching lessons based on what they learn throughout the course.

Education 286 is a direct spin-off of the Professional Development Workshop, with lessons learned from the workshop applied to a formal course and a broader audience. Students who enroll are from many different departments across the sciences and engineering. The course has also become a course taken by the CILS Science Fellows, science graduate students completing education fellowships with the Center for Informal Learning and Schools (CILS), an NSF Center for Learning and Teaching.

3.10. Integrating Research and Education

All our Center members have agreed to commit time to education. Considerable gains have been made in this area, and we continue to focus on involving members in meaningful activities that directly contribute to our educational goals. A few illustrative examples of how we have integrated research and education follow:

- To date, 43 undergraduates have worked on CfAO related research (2002-2004 student cohorts).
- Fifteen high school students and one high school teacher participated in Stars, Sight and Science each year, a course on vision science, astronomy, and optics. A special session on adaptive optics was led by graduate students Jason Porter (Rochester).
- CfAO graduate students and postdocs develop non-technical posters that communicate their research to the Maui technical and educational community, at the annual Maui High Tech Industry Education Exchange.
- The CfAO has developed four new short courses covering CfAO related topics
- CfAO members have developed many new inquiry-based instructional activities, including:
  - Variable star project and inquiry activity (Stars, Sight and Science)
  - Galaxy Project (Stars, Sight and Science)
  - Color and Light (Stars, Sight and Science)
  - Color, Light and Spectra (Mainland Internship Short Course)
  - Color and Light, version 2 (Akamai Short Course)
Table Top Optics (Stars, Sight and Science)
Camera Obscura (Akamai Short Course)
Lenses and Refraction (Akamai Short Course)
Photodiode Activity (Akamai Short Course)
Physiology of the Eye (Rochester Saturday Open Lab)
Color Vision Inquiry (Rochester Saturday Open Lab)
All CfAO retreats, and nearly all CfAO presentations, include an education and human resources component.

3.11. Plans for Year Seven

Annual Professional Development Workshop
This project will continue in the same general format, with an increasing emphasis on formalizing the role of returning participants. We have initiated a research effort to study the professional development of graduate students as they participate in the workshop and incorporate inquiry into their teaching practice.

Mini-Grant Project
Mini-Grants will continue to be offered and promoted within the Center. We will be creating a listing of opportunities and ideas to encourage more proposals.

Stars, Sight and Science
Stars, Sight and Science will be continued, with more development in the assessment of student learning. We will continue the strong link with the Professional Development Workshop, using it to develop instructional activities for Stars, Sight and Science. Stars, Sight and Science is transitioning from a CfAO to a UCSC program, and we will continue to take more steps toward its institutionalization within UCSC in the coming years.

Mainland Internship Program
We have developed a strong internship program, which will be continued with minor refinements. A major focus in the coming years will be to contribute to the knowledge base on the impact of undergraduate research experiences. We are part of a new research study, AScILS (Assessing Science Inquiry and Leadership Skills), which explores how students gain inquiry and leadership skills during research experiences, and how the development of those skills affects their educational and career progress.

Akamai Internship Program
This internship program will continue in the same general structure, with refinements implemented each year. We are currently incorporating a writing element that is interwoven into the entire eight week experience. We will be strengthening the elements of the program preparing students for an industry environment, and developing a “more in-depth” orientation for industry mentors. We will also incorporate broader recruitment to expand the application pool.

Hawaii Island Akamai Observatory Program
Based on the success of the short course implemented in 2004, we are now piloting a full internship program with a 20% time local coordinator. We have significantly increased the participation of Mauna Kea observatories this year and are very hopeful that this program will grow to be part of the observatory community outreach.

**Hartnell Astronomy Short Course**

The first offering of the Hartnell Astronomy Short Course was very successful, and we will be continuing this course in the coming years. We will focus more effort on increasing the institutional support from Hartnell, and developing the academic pathway for Hartnell students to transfer to UCSC to study physics and astronomy.

**Education 286**

This course has grown over the last two years, and will be continued in the coming years. A major goal is for it to be institutionalized by Year 10 of the CfAO, so we will increasingly focus on taking steps in that direction. We encourage other science departments follow the lead of our chemistry department and accept Education 286 as an elective course counting towards a doctoral degree.
4. Knowledge Transfer

4.1. Knowledge Transfer Objectives

The knowledge transfer activities focus on enhancing the Center’s ability to fulfill its research and education goals as summarized in the CfAO mission statement: “To advance and disseminate the technology of adaptive optics in service to science, health care, industry, and education.” In Year 6, the CfAO has continued to emphasize knowledge transfer by employing strategies articulated in its mission statement:

- Increasing the accessibility to AO by the scientific community
- Coordinating and combining research efforts to take advantage of the synergies afforded by the Center mode of operations
- Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology
- Leveraging our efforts through industry partnerships and cross-disciplinary collaboration

In addition, specific objectives for knowledge transfer include: increasing national competence in AO within the scientific, medical, and industrial communities, and enhancing the cohesiveness of the AO technical community, particularly with respect to system performance characterization and optimization.

Performance and management indicators that measure the success of CfAO partnership activities in meeting our objectives include:

- The number of CfAO workshops, and professional training activities that involve non-CfAO participants,
- The level of attendance by non-CfAO personnel at the CfAO summer school,
- The level of attendance by non-CfAO personnel at CfAO workshops,
- The number of institutional members of the AO technical community engaged in the exchange of information concerning system performance and optimization.

4.2. Problems

An ongoing challenge for the CfAO knowledge transfer activity is the exchange of information with industry, both the dissemination of CfAO research results to a broad cross section of the industrial community, and the determination of industrial issues which might best be served by this research. Our strategy during the first 5 years of the Center was to invite a broad cross-section of industry participants to Center events, particularly our Center-wide retreats in the spring and fall of each year. The main goal of this involvement was to catalyze specific research collaborations with industrial partners. In Year 4, we also introduced an Industrial Affiliates Program whereby companies that were not yet prepared to enter into an active collaboration with Center researchers could, for a nominal monetary donation, become stakeholders in the center’s progress and play a more active role in utilizing its’ research or suggesting paths to follow. In Year 5, three companies participated in the Industrial Affiliates Program.
In Year 6, we have begun to concentrate on more specific collaborative activities with industry partners with whom we have established strong ties during the previous 5 years. Based on our experience in the first 5 years, we believe that strong collaborations with specific industry partners are most beneficial to both the industrial and academic participants. We continue to target new industrial partners in specific areas as appropriate. In addition, dissemination of research results to the industrial sector has been improved through several new conferences, topical meetings and panel discussions in areas such as MEMS and vision science. Nevertheless, we continue to view increasing involvement of industry participants in Center research as both a goal and a challenge.

We have carried out a broad range of effective CfAO knowledge transfer activities during year 6 within four focus areas. These activities are summarized in the following sections, along with future plans for the Center’s knowledge transfer program.

### 4.3. Description of Knowledge Transfer Activities

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>CfAO summer school</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Julian Christou</td>
</tr>
<tr>
<td><strong>Participants</strong></td>
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</tr>
<tr>
<td>Organization Name and State</td>
<td></td>
</tr>
<tr>
<td>1 Multiple organizations (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The CfAO holds an annual week-long Summer School on adaptive optics, in Santa Cruz CA. The target audience is graduate students and postdocs, but senior researchers are also welcome to attend. Emphasis is given to topics that are of interest to astronomers and vision scientists alike. Introductory and Advanced AO are presented in alternate years. Each year approx. 100 participants attend. In 2005, 40 of those attending were graduate students, 13 were post docs and 22 were senior researchers.

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Workshops</th>
</tr>
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<tbody>
<tr>
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<td>Multiple leaders (see below)</td>
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<td></td>
</tr>
<tr>
<td>Organization Name and State</td>
<td></td>
</tr>
<tr>
<td>1 Multiple organizations (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The CfAO sponsors workshops each year. These range from large formal sessions at international meetings to smaller special-topics discussions, Workshops in Year 6 included:

1. MEMS Deformable Mirror Workshop, Convener: Bruce Macintosh, held at UCSC, August 19th 2004, 40 participants
2. AO Summer School, UCSC, Aug. 7 to 13 2004 – approx. 100 participants
3. Fall Retreat, Lake Arrowhead, CA. Nov 11 -14 2004 – 148 participants
4. ExAO pre-CoDR Workshop at UCSC, Leader: David Palmer, 10-11 January, 2005, 13 participants
5. Analysis and Simulation Workshop, Center for Adaptive Optics, March 31 – April 1 2005, 31 participants

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Mainland Short Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
<tr>
<td>Participants (add rows as necessary)</td>
<td>1 11 Mainland Interns</td>
</tr>
</tbody>
</table>

CfAO Post docs and graduate students provide a 5 day short course to Mainland interns to prepare interns for their internships at high tech sites on the mainland.

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Optics Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Andy Sheinis</td>
</tr>
<tr>
<td>Participants (add rows as necessary)</td>
<td>1 11 Maui Interns</td>
</tr>
</tbody>
</table>

A short course in optics was organized by Andy Sheinis of CfAO, in conjunction with the faculty at Maui Community College (MCC). Attendees were the CfAO summer interns at Maui who received course credit from MCC. There were 12 participants. The course prepares attendees for their internships at high tech sites on the island.

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Akamai Observatory Short Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
<tr>
<td>Participants (add rows as necessary)</td>
<td>1 11 Interns</td>
</tr>
</tbody>
</table>

Similar to the Maui course and prepares attendees for their internships in high tech sites on the Big Island of Hawaii.

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>New Maui Community College Astro. Lab. Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>John Pye</td>
</tr>
<tr>
<td>Participants (add rows as necessary)</td>
<td>1 Undergraduates</td>
</tr>
</tbody>
</table>

MCC, MEDB and CfAO were awarded $40,495 form the Center for Biophotonics (via NSF funds). This grant will fund the development of a new astronomy lab. course at MCC. John Pye is the MCC PI and will be working with Mark Hoffman at MCC on the AO component.
Knowledge Transfer Activity: Astronomy AO short course at Hartnell Community College
Led by: Anne Metevier and colleagues

**Participants (add rows as necessary)**

<table>
<thead>
<tr>
<th>Organization Name and State</th>
<th>UC Santa Cruz, CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Undergraduates</td>
<td></td>
</tr>
</tbody>
</table>

The lead instructor was Anne Metevier, UC Santa Cruz post doc. She was assisted by Lindsay Pollack, Jennifer Lotz, Liz Espinoza all from UC Santa Cruz and Pimol Moth and Andy Newton from Hartnell College.

Knowledge Transfer Activity: Education 286
Led by: Doris Ash

**Participants (add rows as necessary)**

<table>
<thead>
<tr>
<th>Organization Name and State</th>
<th>UC Santa Cruz, CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 11 Graduate students</td>
<td></td>
</tr>
</tbody>
</table>

This was the third year of this graduate course, sponsored by CfAO that provides an introduction to Inquiry based learning.

Knowledge Transfer Activity: AO test-bed for vision
Led by: David Williams

**Participants (add rows as necessary)**

| 1 Jay and Maureen Neitz, PhD | Medical College of Wisconsin |
| 2 Ed Stone, MD                | University of Iowa           |
| 3 Phillip Kruger              | SUNY School of Optometry     |
| 4 Pablo Artal                 | University of Murcia         |
| 5 Bill Merigan                | University of Rochester      |
| 6 Mina Chung                  | University of Rochester      |
| 7 Wayne Knox                  | University of Rochester      |

A key goal of the CfAO is to make AO broadly accessible to the scientific and medical community. One way we have done this is by making the vision AO systems developed within the CfAO available to research groups outside the CfAO. The Rochester vision AO system has been used by at least 7 different research groups outside the CfAO in the past year.

Knowledge Transfer Activity: AO Manual for vision science
Led by: Jason Porter

**Participants (add rows as necessary)**

| 1 Multiple organizations (see below) |                  |

The CfAO is in the final stages of completing a manual that will contain basic and detailed information on how to design, build, calibrate and implement adaptive optics systems for vision science applications. Our goal is to finish this project by the end of Year 6. The manual will be published in Year 7. Several CfAO members in the vision science and astronomical communities are contributing chapters for this book, which exemplifies the collaborative nature of CfAO. The manual will be published by Wiley Interscience.
4.4. Other Knowledge Transfer Activities

The CfAO web site (http://cfao.ucolick.org) is an important vehicle for knowledge transfer. Information on the CfAO and AO in general is available at this web site, including research projects, education and human resources activities, membership, meetings, publications, distributed software, employment opportunities, and Claire Max’s AO graduate course (http://www.ucolick.org/~max/289C/).

The CfAO publishes a Newsletter that is broadly distributed to inform both internal institutions and external organizations about the highlights of CfAO activities and upcoming events.

The CfAO plays a leading role in the publication of scientific and technical articles on adaptive optics. A list of publications is maintained on the CfAO web site and appears at the end of this Report.

CfAO members play leadership roles in professional societies concerned with adaptive optics, serve on organizing committees for international professional conferences on adaptive optics, and present results of CfAO research. In 2004, the CfAO Associate Director for Knowledge Transfer was named as the Chair of the SPIE Adaptive Optics Working Group, which serves to help disseminate information on AO to the professional optics community, mainly through meetings held during selected major SPIE conferences.

One of our most effective knowledge transfer strategies has been the organization of coordinated national research efforts in key enabling technologies for adaptive optics. The CfAO currently supports coordinated research in MEMS deformable mirror technology, sodium laser guide star systems, and design concepts for AO systems on giant segmented mirror telescopes. Our MEMS effort involves a national consortium of more than a dozen universities, national laboratories, and industrial partners. Our laser development effort includes work on solid state crystal and fiber lasers, and involves at least 9 universities, national laboratories and industrial partners. The work on AO for giant segmented mirror telescopes has involved many CfAO institutions as part of the California Extremely Large Telescope (CELT) project as well as participation on the national GSMT (Giant Segmented Mirror Telescope) Science Working Group. An outcome of these activities in Year 5 was the merging of several efforts in the U.S. and Canada, including CELT, into the Thirty Meter Telescope (TMT) project, which has received a $35M grant from the Moore foundation for preliminary design work. The Director of the CfAO (now emeritus) was named as the Project Scientist for TMT, and CfAO members are the majority participants in the TMT AO Working Group, including the Chair of this group.

The University of Rochester and 5 partner institutions entered the third year of a 5-year, $10M NIH Bioengineering Research Partnership (BRP) to develop and test adaptive optics scanning laser ophthalmoscopes for clinical vision research and patient care. A team led by UC Davis, and including 2 CfAO member institutions, Indiana University and LLNL, entered the second year of a 5-year, $5M NIH BRP to develop and test
instrumentation combining adaptive optics and optical coherence tomography for clinical vision research and patient care.

Collaborative program development has been a successful strategy for leveraging Center resources to enable research and development of adaptive optics beyond what would be possible with CfAO funding alone. This strategy is also a highly effective means of knowledge transfer since the new collaborative programs include participants both inside and outside the Center. The major collaborative program development activities in Year 6 were in the areas of ExAO, AO instruments for TMT, ophthalmic instrumentation and MEMS. For example, in the area of ExAO, the theme has been responsible for bringing together additional institutions in the US and Canada, including the Hertzberg Institute of Astrophysics, the American Museum of Natural History, and the Université de Montréal, to work on system design, simulation and modeling of ExAO systems for the Gemini Telescope and the Thirty Meter Telescope. A major outcome of this activity in Year 6 was the completion of a four-volume conceptual design study for the Gemini Observatory and a proposal to build this ~$20M instrument.

In connection with the EHR Professional Development Workshop, in Year 6 a Community Networking Session was again cosponsored by local industrial organization in Maui. This session provided an opportunity for CfAO grad-students and post-docs to present information on CfAO research to both educational and industrial communities in Maui. An intern program for Hawaiians was continued in Year 6 with 22 interns. A CfAO researcher in collaboration with Maui Community College faculty taught an introductory optics course to the interns prior to their taking up their internships at industrial locations in Maui and the Big Island. Other educational activities on Maui and the Big Island have been described in Section 4.3

4.5. Knowledge Transfer Activities - Future Plans

We plan to maintain our program of information dissemination while enhancing particular aspects and incorporating new efforts. Continuing to enhance the CfAO web site through additional content and improved organization will be an area of emphasis. We will continue to encourage our researchers to publish in a timely mode in the peer reviewed literature. We are planning a manual on the design, implementation, characterization and optimization of AO for vision applications to be published in Year 7.

In vision science we are developing a new generation of portable vision science AO systems that will be taken directly to partner medical facilities, such as the Doheney Eye Institute at USC, for evaluation in a clinical environment. This will extend the scope of possible collaborative activities by accessing unique capabilities and conditions at the partner sites, while further broadening the reach of AO into the clinical community.

Specific areas of emphasis in collaborative program development in Year 7 will include AO for ophthalmic instrumentation, AO for giant segmented mirror telescopes, and MEMS development. We will continue to explore a stronger connection with the new NSF Center for BioPhotonics at UC Davis in an area of mutual technical and scientific
interest, most likely in the applications of AO to confocal microscopy for \textit{in vitro} biological research, \textit{in vivo} endoscopic imaging, and/or medical uses of CfAO fiber laser technology. The partnership with the Air Force Maui Optical Station that combines technical research and development with new education and human resource activities will continue to be developed in Year 7.
5. Partnerships

5.1. Partnership Objectives

The fundamental objective of our partnership activities is to enhance the Center’s ability to fulfill its research and education goals. The CfAO is pursuing this objective through strategies articulated as part of its mission statement.

- Leveraging our efforts through industry partnerships and cross-disciplinary collaborations
- Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology

In addition, specific objectives for partnerships include:

- Stimulating further investment by government and industry sources in AO research and development
- Catalyzing the commercialization of AO technologies leading to technological advancements relevant to CfAO research objectives and enabling broader use of AO.

Performance and management indicators that measure the success of CfAO partnership activities in meeting our objectives include:

1) The number of partner institutions engaged in active collaboration with the Center,
2) The number and scope of CfAO projects involving cross-disciplinary collaborations,
3) The number and amount of additional investment by government and industry sources in AO research and development,
4) The number and scope of AO commercialization activities in which the CfAO plays a role,
5) The number of institutional members of the AO technical community engaged in the exchange of information concerning system performance and optimization.

5.2. Problems

An ongoing challenge for CfAO partnership activities is the development of new industrial partnerships, particularly in areas involving highly competitive commercial markets, such as ophthalmic instrumentation. We are continuing to seek guidance on best practices in the commercialization of the type of medical imaging instrumentation being developed by the Center.

5.3. Description of Partnership Activities

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Development of Advanced Ophthalmic Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>David Williams</td>
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<table>
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<tr>
<th>Participants</th>
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<tbody>
<tr>
<td>Name of Organization</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Lawrence Livermore National Laboratory, the University of Houston, the University of California at Berkeley, the Doheny Eye Institute at USC, and the Schepens Eye Research Institute at Harvard University</td>
</tr>
</tbody>
</table>
CfAO’s PI at the University of Rochester is leading a NIH Bioengineering Research Partnership (BRP), which was awarded a 5-year grant in 2003 at the level of $10 million. Six partner institutions share the funds; these are the University of Rochester, Lawrence Livermore National Laboratory, the University of Houston, the University of California at Berkeley, the Doheny Eye Institute at USC, and the Schepens Eye Research Institute at Harvard University. The partnership will develop and assess the value of adaptive optics scanning laser ophthalmoscopes for clinical vision research and patient care by studying the following: neovascularization in age-related macular degeneration and diabetic retinopathy; photoreceptors in retinal degenerative disease such as retinitis pigmentosa; ganglion cell bodies in glaucoma; individual retinal pigment epithelial cells; and blood flow in the smallest retinal capillaries. Work is ongoing on four new scanning laser imaging instruments using MEMS based adaptive optics developed by the CfAO. In a related development, the U.K. company, Optos, has made plans to incorporate adaptive optics in a wide field scanning laser ophthalmoscope using intellectual property held by Rochester and Houston.

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Clinical testing of MEMS AO phoropter</th>
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<tbody>
<tr>
<td>Led by</td>
<td>David Williams</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Participants</th>
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</thead>
<tbody>
<tr>
<td>Name of Organization</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Lawrence Livermore National Laboratory, Sandia National Laboratory, Boston Micromachines Corporation, Wavefront Sciences, Bausch &amp; Lomb</td>
</tr>
</tbody>
</table>

Based on activities sponsored by CfAO, in 2002 a collaborative team led by LLNL was awarded ~$2.7M over 2 years through the DOE Biomedical Engineering Program to develop and test clinical ophthalmic instruments using MEMS adaptive optics. In CfAO Year 4, the team completed the integration and testing of the first clinical prototype vision science instrument – a portable, MEMS-based adaptive optics phoropter, which can be used to measure and correct the high order aberrations in the human eye, thereby enabling the development of clinical procedures for prescribing new vision correction technologies for the permanent correction of high-order aberrations, such as custom laser refractive surgery and custom contact lenses. This instrument was selected for a 2003 R&D 100 award, through a program sponsored by the Chicago-based, R&D Magazine, which recognizes the 100 most technologically significant inventions in the U.S. each year. During the past year the phoropter has been undergoing further testing and refinement at the University of Rochester. The most important refinement has been the upgrade of the MEMS deformable mirror from Boston Micromachines, which has been changed to a version with increased dynamic range – ~4 microns, compared with ~2.5 microns for the previous mirror. This increase in dynamic range is crucial for clinical operability, and has set the stage for clinical tests of the instrument, which are planned to begin later this year at Bausch & Lomb. Several companies have expressed an interest in potential commercialization of the MEMS-based adaptive optics phoropter. These include Carl Zeiss Meditec, Ciba Vision, Wavefront Sciences and Reichert, the company with the largest market share worldwide of the phoropter business.
Partnership Activity | Optical Coherence Tomography with Adaptive Optics
---|---
Led by | John Werner

### Participants

<table>
<thead>
<tr>
<th>Name of Organization</th>
<th>List Shared Resources (if any)</th>
<th>Use of Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC Davis (Lead)</td>
<td></td>
<td>Demonstrate the clinical utility of the combination of AO and optical coherence tomography (OCT)</td>
</tr>
</tbody>
</table>

1. UC Davis, LLNL, University of Indiana, Duke University, the Doheny Eye Institute at USC, Carl Zeiss Meditec, Inc.

Based on research activities initially sponsored by CfAO, UC Davis led a successful proposal in 2003 for a Bioengineering Research Partnership (BRP) Grant for $5.5 million over 5 years. The proposal focuses on demonstrating the combination of AO and optical coherence tomography (OCT). The clinical utility of this combination, which should enable high-resolution imagery of the living retina with extremely high contrast ratios, will be evaluated. Achieving the highest possible contrast ratios in three-dimensional retinal images is important for the accurate visualization of many clinically important structures in the retina that have intrinsically low scattering cross sections, such as ganglion cells, which are damaged by glaucoma. Joint recipients of the grant are UC Davis, LLNL, Indiana University and Carl Zeiss Meditec, Inc. (formerly Zeiss Humphrey Systems). During the second year of this project, we have integrated AO with two distinct types of OCT systems at UC Davis and Indiana University. In a related activity, CfAO researchers at LLNL have received a grant from the DOE Biomedical Engineering Program to develop an OCT system with AO for the Doheny Eye Institute at USC.

### Partnership Activity

**Micro-electro-mechanical systems**

Led by Scot Olivier, Don Gavel

### Participants

<table>
<thead>
<tr>
<th>Name of Organization</th>
<th>List Shared Resources (if any)</th>
<th>Use of Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>A consortium, organized by the CfAO, to develop MEMS deformable mirror technology for adaptive optics for vision science and astronomy</td>
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</table>

The CfAO continues to support and coordinate the work at several universities (UC Berkeley, Boston University, UC Davis, Stanford University), national laboratories (LLNL, SNL, AFRL, JPL) and industrial partners (Lucent, Boston Micromachines, Cronos, MEMX, Iris AO, AOptix, MicroAssembly Technologies) to develop MEMS deformable mirror technology for adaptive optics suitable for application to vision science and astronomy. In Year 6, Boston Micromachines delivered several 140-actuator mirrors with ~4 micron stroke, and is working on a version with 6 micron stroke. AOptix has delivered several 37-actuator bimorph mirrors with a 10-mm clear aperture and ~30 micron stroke for focus correction (amplitude falls with ~square of spatial frequency for higher order modes). Many other partners continue to work on development of mirrors...
with high stroke. Boston Micromachines has also delivered several 1000-actuator mirrors for testing in the ExAO test bed at the UCSC Laboratory for AO.

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Lasers</th>
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<tbody>
<tr>
<td>Led by</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Edward Kibblewhite; 2. Deanna Pennington</td>
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</tbody>
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<table>
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<tr>
<th>Participants</th>
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</thead>
<tbody>
<tr>
<td>Name of Organization</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>1 Lite Cycles, Coherent Technologies, The AFRL at Kirtland Air Force Base, LightWave Electronics.</td>
</tr>
<tr>
<td>2 European Southern Observatory Hampton University, Ionas, IRE Poulus Group, TuiOptics, Fibercore and the IPHT fiber institute in Jena, Germany.</td>
</tr>
</tbody>
</table>

Under CfAO funding, the University of Chicago worked with Lite Cycles to produce improved solid state laser heads for a sum-frequency laser based on a design originally from MIT Lincoln Labs. The development and testing phase of the laser was successfully completed in Year 5 and the laser was shipped to Mt. Palomar Observatory for deployment, which was successfully completed in Year 5. Coherent Technologies Inc. has completed a contract from Gemini Observatory to develop another approach for an improved laser head for this general class of laser, and they have delivered and deployed this system on the Gemini North telescope. AFRL worked with Lightwave Electronics on another laser head concept for this class of laser, and successfully tested a 20 W version of this laser on the sky at the Star Fire Optical Range at the AFRL. The NSF awarded a grant to the Keck Observatory for an industrial solid state laser to be placed on the Keck I Telescope, and Keck is evaluating industry bids for this contract in conjunction with Gemini Observatory.

LLNL has a project within the CfAO to study fiber lasers. Complementary aspects of this work have been supported by internal funding at LLNL. An international collaboration has been established with the European Southern Observatory to jointly pursue this research. This has resulted in the provision of equipment and manpower by ESO to complete the research. Significant industrial contacts have been established to produce the new custom technology components required for this research, namely Ionas, IRE Poulus Group, TuiOptics, Fibercore and the IPHT fiber institute in Jena, Germany. Fiber laser amplifiers with output power over 10 W at 2 infra-red wavelengths and excellent beam quality have been demonstrated. Current work is concentrating on sum frequency combination of the output of these fiber lasers to produce light at 589 nm, suitable for fluorescence of atomic sodium. LLNL has been awarded a grant from the NSF Adaptive Optics Development Program to extend this fiber laser work to a pulsed format more suitable for use on giant (30-m class) telescopes that will require multiple laser beacons.

5.4. Other Partnership Activities

In the area of design of AO systems for giant segmented telescopes, CfAO previously co-sponsored a working group with NOAO to produce a national AO technology
development roadmap. This roadmap was used by the NSF to initiate an Adaptive Optics Development Program, which began in 2004 with an initial budget of ~$3M which was used to support 6 projects. CfAO researchers lead 2 of these projects, and 2 others involve CfAO personnel. In addition, many CfAO institutions have been active in working on design concepts for AO systems on giant segmented mirror telescopes as part of the California Extremely Large Telescope (CELT) project sponsored jointly by the University of California and CalTech. In Year 5, the CELT team joined with the U.S. and Canadian national efforts in giant segmented telescope design. The combined effort is being called the Thirty Meter Telescope (TMT) project, and support for a preliminary design phase of this project at the level of $35M has been received from the Moore foundation. The national science foundations in the U.S. and Canada have also been asked to contribute a similar amount, and these agencies are currently considering these proposals. An AO working group for TMT has been formed and CfAO members make up the majority of this group, including the chair. It is readily evident that the work on TMT AO design is being coordinated directly with the CfAO Theme on AO for Extremely Large Telescopes.

5.5. Partnership Activities - Future Plans

- Continue to extend our leveraged partnership activities in the area of the development and assessment of prototype clinical ophthalmic instrumentation.
- Continue to drive the development of MEMS for vision science and astronomical applications through partnerships coordinated within the framework of our national MEMS consortium.
- Continue to develop a partnership with the Air Force Maui Optical and Supercomputing Site that combines technical research and development with education and human resource development in Hawaii.
- Focus on design concepts for AO systems on giant segmented telescopes in partnership with the TMT project.
6. Diversity

6.1. Overall objectives.

The CfAO has the following goals for broadening participation to increase CfAO diversity:

- Increase participation of underrepresented groups in CfAO research and education activities
- Advance students from underrepresented groups into CfAO related fields through participation in CfAO activities

6.2. Performance and management indicators

TOOLS. Implement activities and programs that broaden access to CfAO related fields.

- Programs developed, implemented, and documented
- Activities (within programs or stand-alone) developed, implemented, and documented
- Courses developed, implemented, and documented
- Progress in sustaining programs, activities, and courses beyond CfAO Year 10
- New educational pathways stimulated by, or spun off of, programs, activities, or courses

PRACTICES. Involve CfAO members in CfAO EHR programs and activities, and more specifically in educational practices that broaden participation.

- Number of CfAO members teaching or mentoring in CfAO EHR programs
- Number of CfAO members that incorporate new teaching or mentoring strategies into their practice
- Number of CfAO graduate students and postdocs who implement inquiry based teaching strategies

PARTNERSHIPS & LINKAGES. Develop linkages and partnerships that broaden participation in the CfAO and CfAO sites.

- Linkages between CfAO sites and organizations that serve significant numbers of students from underrepresented groups
- New pathways that broaden access to CfAO and CfAO related fields
- Joint activities, programs, and courses developed and implemented by CfAO and organizations that serve students from underrepresented groups
- New mechanisms for engaging relevant communities in the CfAO and CfAO related fields

PEOPLE. Broaden participation of CfAO and CfAO fields by advancing students from underrepresented groups.

- Number of underrepresented undergraduates participating in CfAO activities (research and education)
- Number of underrepresented undergraduates retained in STEM
- Number of underrepresented undergraduates advanced into CfAO, and CfAO related, graduate programs

97
• Number of underrepresented graduate students participating in CfAO activities (research and education)

6.3. Challenges

The challenge faced by the CfAO can be seen throughout U.S. STEM graduate programs: women, underrepresented minorities, and U.S. citizens in general, are not pursuing doctoral degrees at the level appropriate to their representation in the U.S. college age population. For some of our CfAO sites, the challenge is finding students from underrepresented groups. For other sites, it lies in finding U.S. students from any ethnic group or gender. For the past few years we have focused our efforts on training undergraduates through our internship programs. This year we are beginning to see the fruits of our efforts as our CfAO undergraduate interns move onto graduate studies.

6.4. Activities and Impact

Diversity initiatives and activities are integrated throughout the CfAO EHR theme. However, the most significant effort is at the undergraduate level through CfAO’s internship programs and short courses. The CfAO has chosen to focus on the undergraduate (including community college) level and the transition from the bachelor’s level into graduate studies due to the low entry rates and persistence rates of underrepresented groups in CfAO-related fields at the undergraduate level. Although we continue our recruitment efforts at the graduate level, our early efforts made it clear that with so few prospective graduate students from underrepresented minority groups, our efforts would be most effective at the undergraduate level.

The following programs and activities (fully described in Education section of this report) are focused on increasing the diversity of the CfAO and CfAO related fields:

6.4.1. Mainland Internship Program

Summer research experiences for undergraduates (4-yr and community college). The goal of the program is to retain and advance students from underrepresented groups in CfAO related fields. From 2002-2004, 43 students have been accepted into the program (67% underrepresented minority [URM]; 63% female; 95% URM or female). Of those 43, at least 37 (86%) and possibly as many as 40 (3 have not responded to our recent queries) are still on an STEM education/career path. Five of these students began graduate school in 2004 (3 women; 2 URM).

In June 2005, an additional 10 students were accepted into the program. Of these 10, 6 are women, 8 are URM; 9 are either women or URM.

6.4.2. Akamai Internship Program

Summer research experiences for college students who are Hawaii residents. The goal of this program is to retain and advance students in technical and scientific fields relevant to the state of Hawaii. In 2003-2004, 18 students were accepted into the program (56% URM; 28% female; 72% URM or female; 100% Hawaii residents (or Hawaii residents studying on the mainland); 17 (94%) community college students). Two students have
now transferred to a 4-year institution, five have entered the STEM workforce in full-time positions, three are still enrolled in college and hold part-time positions in the STEM workforce. In June 2005 an additional 13 students were accepted into the program. Of the 13, 2 are women; 6 are URM; and 6 are either women or URM.

6.4.3. Akamai Observatory Short Course
An intensive one-week course to prepare students for observatory internships and/or motivate them to participate in future internships. The course was offered for the first time in June 2004. Seventeen students enrolled in the course, 16 Hawaii state residents; 7 URM; 4 women; 10 URM or women.

6.4.4. Hawaii Island Akamai Observatory Internship Program
An expansion of the Akamai Observatory Short Course which was piloted in 2004. In 2005, we accepted the first cohort of eleven students into the program, all of whom are Hawaii residents or are from Hawaii studying on the mainland. Of the eleven, 3 (27%) are URM; 3 (27%) are women; and 5 (45%) are either URM or women. We will increase our effort in 2006 to increase the number of women and underrepresented minorities.

6.4.5. Hartnell Astronomy Short Course
Intensive one-week course to motivate students to pursue astronomy/physics, and apply to internships in the future. The course was offered for the first time in June 2004, 19 students enrolled (6 women; 10 URM; 14 URM or female). Recruitment was from Hartnell Community College, a Minority Serving Institution.

6.4.6. CfAO Graduate Fellowship
Fellowship for incoming graduate students from underrepresented groups at CfAO sites. The goal is to broaden participation of underrepresented groups in CfAO research. We have awarded the fellowship to four graduate students: 1 at UCLA affiliated with A. Ghez (U.S. citizen, white, female), and 3 at UCSC in electrical engineering (2 Hispanic male U.S. citizens; 1 Hispanic male non-U.S. citizen).

6.4.7. CfAO Post-Bac Fellowship
Fellowship for prospective graduate students with BA/BS degrees. The goal is to advance underrepresented minority students into CfAO graduate programs. We piloted this program in 2004, cost-sharing the fellowship with Keck Observatory through their AODP grant from the NSF. The student spent the 2004-2005 academic year preparing for graduate school and participating in research under the supervision of Jerry Nelson (UCSC) and Sean Adkins (Keck). He has been accepted into the engineering doctoral program at UCSC and will begin his graduate studies in Fall 2005.

6.4.8. Participation in minority serving organizations
The CfAO has participated in the SACNAS (Society for Advancement of Chicanos and Native Americans in Science) Conference for the past three years. The outcomes include applications to our Mainland Internship Program and closer connections to other minority serving organizations. For example, through the SACNAS Conference we met representatives from HACU (Hispanic Association of Colleges and Universities), who funded three of our Hispanic interns, and directly recruited two of our interns in 2004. In
2005 HACU is supporting four interns and was responsible for the direct recruitment of at least six students.

6.4.9. **Stars, Sight and Science:**

Four-week residential science program for high school students. The goal of this program is to motivate high school students to pursue science in college. 62 students have been through the program (2001-2004), 44 female; 50 URM. The female or URM groups altogether totaled 58. Of these, 21 have entered college or will be entering this fall.

6.5. **2004-2005 Recruitment Study: Activities and Lessons Learned**

A significant amount of time and resources at the CfAO is spent each year in the identification and recruitment of high achieving students from underrepresented groups, including women and minorities. In 2004-2005 we closely monitored our recruitment activities and the yield of students produced from these efforts. Our goal from this study of recruitment efforts was to identify the most productive way to use our resources in the future. We focused on our most mature program, the Mainland Internship Program, because we have developed a range of recruitment activities for this program, and these recruitment efforts cross-over with the more general recruitment activities for our graduate programs.

Recruitment efforts for the Mainland Internship Program include college visits, attendance at national conferences, and a range of other activities that put the CfAO in direct contact with students. The following points summarize recruitment outcomes:

- Overall applications were much lower in 2005, with only 52 complete applications, compared to 89 complete applications in 2004. The reason is not yet apparent. However in 2005 we didn’t utilize the STC combined effort applications, which were included in the total from last year.
- Attendance at national conferences (SACNAS and NSBE/NSBP) did not yield any students this year. (NSBE=Nat’l Society of Black Engineers; NSBP=Nat’l Society of Black Physicists)
- In 2004, 4 interns who participated in the Mainland Internship were recruited through the SACNAS conference. A major difference was that in 2004 we organized and gave a scientific symposium, but did not for the 2005 recruitment (our proposal for a symposium was not accepted by SACNAS, presumably because we had just given one the year before). We will re-consider spending resources on attending those conferences where we are not giving a scientific talk or running a symposium.
- The CfAO’s Saturday Open Labs program did not yield any students this year. In 2004 two students were recruited through Saturday Open Labs. The reason for the difference between 2004 and 2005 is not apparent, but since the numbers are small this may just be a statistical fluctuation.
- Two students in the 2005 Mainland Internship Program came from the Hartnell Astronomy Short Course.
- Our “Leading with Research” effort, which sent past interns out to colleges and student organizations, yielded 1 student for the Mainland Internship Program.
• Our HACU partners recruited 14 students to apply, and 5 have been accepted in the Mainland Internship Program, making this the most successful recruitment strategy in 2005. In 2004 we received 4 applications through HACU recruitment, but none of them was qualified. HACU supported three students (recruited through other mechanisms) and did a site visit on the last day of the program, and came away with a great deal of enthusiasm for the program, which probably translated into a stronger recruitment effort on their part.

• We are not aware of any applications to our graduate programs this year, or in any past years, that can be attributed to our participation in conferences. Grad school applications come about because of our sustained contact with students in Short Course plus Internship situations.
Table 6.1 Recruiting Activities: Fall 2004-Spring 2005

<table>
<thead>
<tr>
<th>Where</th>
<th>Date</th>
<th>Description of Event</th>
<th># who filled information cards</th>
<th>Number of Complete Apps</th>
<th>Number Accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austin, TX</td>
<td>5-Oct</td>
<td>SACNAS Conference Booth: Past interns attended</td>
<td>25</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5-Feb</td>
<td>NSBE/NSBP Conference Booth: Past interns attended</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Florida</td>
<td>5-Oct</td>
<td>Past research experience talk by E. Hernandez</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Oxnard Community College</td>
<td>2-Dec-04</td>
<td>&quot;Leading with Research&quot; - Presentation by C. Andres Internship. Presentation by M. Bell. Served Pizza for lunch time presentation and visited 4 classrooms for 10-minute presentations</td>
<td>39</td>
<td>5</td>
<td>2 accepted and 2 on waiting list</td>
</tr>
<tr>
<td>Hartnell Community College</td>
<td>21-Jan</td>
<td>MESA Lunch Presentation as part of Annual Career day at Canada</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Canada Community College</td>
<td>21-Jan</td>
<td>Afternoon MESA Presentation &quot;Leading with Research&quot; and internship presentation by C. Andres</td>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Skyline Community College</td>
<td>5-Feb</td>
<td>Saturday Open Lab with 1 U of Rochester student and 5 UMBC students</td>
<td>6</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>U of Rochester, NY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.2. How students reported finding out about the 2005 Mainland Internship

<table>
<thead>
<tr>
<th>Applicant reported source reported on application</th>
<th>Students applied (complete applications)</th>
<th>Students accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI presentation</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Faculty member/counselor</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>SACNAS</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>HACU</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>Internet</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>CfAO representative</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Big Island Short Course</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Hartnell Short Course</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>MESA</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Sat. Open Lab</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>52</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>

* note that some accepted students identified multiple sources. The total represents the actual number of completed apps and accepted students

6.6. Diversity Plans for CfAO Year 7

6.6.1. General Comments

Many of the above diversity activities will be continued in Year 7. Our study of recruitment efforts in Year 6 indicates our most successful activities are the short courses, college visits, our collaboration with HACU, and direct recruitment by our faculty and staff. Our participation in conferences did not yield any accepted students this year, despite strong CfAO attendance and a fully staffed booth. In the past in addition to the booths, we have given scientific talks at these conferences, and have had much better success in identifying strong candidates for our program. In future years we will carefully consider our participation in conferences, perhaps only attending if we have the opportunity to give a scientific talk or lead a symposium.

We have identified several areas for improvement in the coming years. The Akamai program needs a better representation of women, both on the Big Island and Maui. Our partners for both programs are currently working with us to identify new strategies to improve our recruitment.

6.6.2. Graduate student recruitment

As described earlier in this section, graduate student recruitment has been an ongoing challenge for us. We have found our most successful strategy to be that of “grow your own” through recruitment and retention of students at the undergraduate level, and we will continue doing this in the coming years.
Our CfAO interns are advancing through their undergraduate education, and many are now becoming prospective graduate students. In the coming years, we will be assisting them in the graduate application process and encouraging them to apply to CfAO sites.

6.7. Impact of Diversity efforts and Challenges
The challenges have already been described in Section 6.1.3. and impacts in Section 6.2.1
7. MANAGEMENT

7.1. Infrastructure Aspects

7.1.1. Center Organization

Professor Claire Max accepted the position of the Director of the Center for Adaptive Optics (CfAO) in January 2005. Professor Jerry Nelson, the Center Director since its inception, decided to step down because of his new responsibilities as the Project Scientist for the 30-meter telescope Project. Professor Nelson remains a member of the Executive Committee and a participant in Theme 2 – AO for Extremely Large Telescopes. Dr. Donald Gavel has accepted the position of Associate Director for Theme 2, which was previously held by Professor Max. Dr. Chris Le Maistre will continue in his position as Managing Director. See Organization Chart – Appendix B.

The Center’s External Advisory Board and its Program Advisory Committee endorsed the appointment of Claire Max as Director of the CfAO and the changes described above.

7.1.2. Performance and Management Indicators

No changes from the previous reporting period.

7.1.3. Problems and Solutions

The adjustment made to the Management structure has already been discussed.

7.2. Center Integration – Processes implemented

No changes from previous reports.

7.3. Internal and External Committees

7.3.1. Internal Oversight Committee – University of California Santa Cruz

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Burney Le Boeuf</td>
<td>Associate Vice Chancellor, Research</td>
</tr>
<tr>
<td>2 David Kliger</td>
<td>Acting Provost</td>
</tr>
<tr>
<td>3 Steve Kang</td>
<td>Dean, School of Engineering</td>
</tr>
<tr>
<td>4 Joseph Miller</td>
<td>Director, UCO/Lick Observatory</td>
</tr>
<tr>
<td>5 Francisco Hernandez</td>
<td>Vice Chancellor, Student Affairs</td>
</tr>
</tbody>
</table>

The Committee meets at least once a year. Additionally, the Center Director meets regularly with the Director of the UCO/Lick Observatory, who conveys concerns or issues to the Oversight Committee as needed.

7.3.2. External Committees

The Center has two external committees:
7.4. Changes to the Center’s Strategic Plan

The overall plan for the life of the NSF Science and Technology remains unaltered. There has been a change in emphasis within Theme 2 with an intensified focus on development of high stroke MEMS deformable mirrors. The performance and cost effective solutions for both the Thirty Meter Telescope and the high contrast extreme AO coronagraph are dependant on the commercial availability of these mirrors. In Theme 3 – Extreme Adaptive Optics, the uncertainty with respect to Gemini Observatory funding for the building of the high contrast AO coronagraph has required us to create a contingency plan for Year 7 in the event that the funding is unavailable. We have done so.

The Center for Adaptive Optics is entering its seventh year and Center management has initiated Center-wide meetings to develop a Strategic Plan for the long-term future of the Center after NSF funding ceases in Year 10. The kick-off meeting for this effort took place in early August 2005, and it will continue in its next phase at the CfAO fall retreat.

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**The Program Advisory Committee**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dr. Michael Lloyd-Hart</td>
<td>University of Arizona</td>
</tr>
<tr>
<td>2 Dr. Mark Colavita</td>
<td>Jet Propulsion Laboratory, Pasadena, CA</td>
</tr>
<tr>
<td>3 Dr. Stanley Klein (Chair)</td>
<td>University of California, Berkeley, CA</td>
</tr>
<tr>
<td>4 Dr. Malcolm Northcott</td>
<td>AOPTIX Technologies, Campbell, CA</td>
</tr>
<tr>
<td>5 Carrol Moran</td>
<td>University of California, Santa Cruz, CA</td>
</tr>
<tr>
<td>6 Dr. Rodney Ogawa</td>
<td>University of California, Santa Cruz, CA</td>
</tr>
</tbody>
</table>

**The External Advisory Board**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dr. Christopher Dainty</td>
<td>National University of Ireland</td>
</tr>
<tr>
<td>2 Dr. Ray Applegate</td>
<td>University of Houston, TX</td>
</tr>
<tr>
<td>3 Dr. Robert Byer (Chair)</td>
<td>Stanford University, CA</td>
</tr>
<tr>
<td>4 Dr. Thomas Cornsweet</td>
<td>Visual Pathways Inc, Prescott, AZ</td>
</tr>
<tr>
<td>5 Dr. Norbert Hubin</td>
<td>European Southern Observatory, Munich</td>
</tr>
<tr>
<td>6 Dr. Fiona Goodchild</td>
<td>University of California, Santa Barbara, CA</td>
</tr>
<tr>
<td>8 Dr. Sidney Wolff</td>
<td>National Optical Astronomy Observatories, Tucson, AZ</td>
</tr>
<tr>
<td>9 Dr. Robert Fugate</td>
<td>Air Force Research Labs, Albuquerque, NM</td>
</tr>
<tr>
<td>10 Dr. David R. Burgess</td>
<td>Boston College, Boston, MA</td>
</tr>
</tbody>
</table>
8. CENTER-WIDE OUTPUTS AND ISSUES

8.1. Center Publications

Year 6 Peer Reviewed Publications


**Year 6 Peer Reviewed Publications: Submitted Only**


**Book Chapters**


**Year 6 Publications: non- peer reviewed**


Conferences


8.2. Other Dissemination Activities

Talks and Lectures and Colloquia by CfAO Members

Note: This is not a complete list.

1. Blake Lin, “Selectively Addressed MEMS Deformable Mirror Arrays for Adaptive Optics,” poster presentation to industrial members of the Berkeley Sensor & Actuator Center (BSAC) at the BSAC Industrial Advisory Board Meeting, 8 March, 2004, Univ. of California, Berkeley. A write up with copies of the visuals presented incorporated into a technical digest.


6. Andrea Ghez: 06/07/04 The Formation of Supermassive Black Holes, Aspen, CO

7. Andrea Ghez: 06/25/04 Massive Stars in Interacting Binaries, Quebec, Canada

8. Andrea Ghez: 02/09/05 Planet Formation and Detection, Aspen Center for Physics

9. Andrea Ghez: 03/21/05 American Physical Society Meeting, Los Angeles, CA

10. Andrea Ghez: 04/02/05 40 Years of Infrared Astronomy: A Tribute to Eric Becklin, Los Angeles, CA

11. Andrea Ghez: 04/13/05 American Astronomical Society Division of Dynamical Astronomy Meeting, Santa Barbara, CA

12. Andrea Ghez: 05/02/05 Sectional Meeting of Astronomy at the National Academies, Washington DC

13. Andrea Ghez: 05/03/04 Cornell University, Salpeter Lecture, Department of Physics
14. Andrea Ghez: 05/19/04 Tel Aviv University, Department of Physics
15. Andrea Ghez: 10/05/04 Whittier College, Department of Physics and Astronomy
16. Andrea Ghez: 02/28/05 University of California Davis, Department of Physics
17. Andrea Ghez: 03/29/05 University of Texas at Austin, Department of Astronomy
18. Andrea Ghez: 03/30/05 University of Michigan, Department of Physics
19. Andrea Ghez: 04/27/05 Department of Terrestrial Magnetism, Astrophysics Group
20. Andrea Ghez: 04/27/05 University of Maryland, Department of Astronomy
22. Claire Max: December 2004, Director’s Distinguished Lecturer, Lawrence Livermore National Laboratory
23. Claire Max: March 15, 2005, Colloquium at Institute for Advanced Study, Princeton NJ
24. Claire Max: April 14, 2005, Colloquium at Johns Hopkins University, Baltimore MD
25. Claire Max: April 27, 2005, Colloquium at the University of San Francisco
26. Anand Sivaramakrishnan and Remi Soummer lectured at the Michelson Summer School at Caltech in July 2004

**Workshops and Courses Organized by the CfAO**

1. MEMS Deformable Mirror Workshop, Convener Bruce Mackintosh, UCSC, August 19th 2004
2. AO Summer School, UCSC, Aug. 7 to 13 2004
3. Fall Retreat, Lake Arrowhead, CA. Nov 11 -14 2004
4. ExAO pre-CoDR Workshop at UCSC, Leader: David Palmer, 10-11 January, 2005
5. Analysis and Simulation Workshop, Center for Adaptive Optics, March 31 – April 1 2005
6. "Adaptive Optics: Analysis and Modeling” Meeting Chair Brent Elllebroek, Program Chairs Julian Christou and Domenico Bonacinni. OSA Topical Meetings, Charlotte, NC; June 2005
9. CATS Workshop on Extragalactic Adaptive Optics, Center for Adaptive Optics, UC Santa Cruz, August 7 2005
**Miscellaneous Activities:**

1. Laboratory for Adaptive Optics Dedication Ceremony, UC Santa Cruz, May 17 2005

2. Ellerbroek, Brent Updates to an AO simulation code (CIBOLA) for the CfAO website. [http://cfao.ucolick.org/software/cibola.php](http://cfao.ucolick.org/software/cibola.php)

3. LeMignant, David: Many technical aspects and details of LGS operations and LGS science operations have been made available to the community through our web page: [http://www2.keck.hawaii.edu/optics/lgsao/](http://www2.keck.hawaii.edu/optics/lgsao/)

4. Melbourne, Jason organized a weekly “compact galaxy lunch” at UCSC, 2004-2005


6. Pennington, Deanna: In order to handle the high peak powers generated in a 938 nm pulsed fiber amplifier, we developed a design for an air-clad. Fabrication of this device required a collaborative agreement to be established between Nufern (manufacturer for our 938 nm core) and Crystal Fiber (a Danish company that makes photonic crystal fiber devices). This partnership will enable the production of unique fibers for LGS applications.

7. Pennington, Deanna: Nufern has expressed an interest in licensing LLNL fiber laser technologies. This would enable a commercial amplifier provider for these systems.

8. Pennington, Deanna: Working with Actinix Corporation to develop other applications for the fiber laser technologies developed here, and have jointly applied for these. This funding, if received, would enable Actinix to license our technologies and become a commercial provider.

9. Poyneer, Lisa and Bruce Macintosh spatially-filtered WFS concept being applied to high-power laser applications at LLNL.

### 8.3. Awards and Other Recognition

<table>
<thead>
<tr>
<th>Recipient 1</th>
<th>Reason for Award</th>
<th>Award Name and Sponsor</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claire Max</td>
<td>For her contributions to the theory of laser guide star adaptive optics and its application in ground-based astronomy to correct telescopic images for the blurring caused by light passing through the atmosphere.”</td>
<td>Ernest Orlando Lawrence Award in Physics, US Dept of Energy</td>
<td>11/8/04</td>
</tr>
<tr>
<td>David Williams and Heidi Hofer</td>
<td>Best Article in Optics and Photonics News</td>
<td>Archie Mahan Prize awarded by the Optical Society of America</td>
<td>October 2004</td>
</tr>
<tr>
<td>David Williams</td>
<td>Recognition for his incomparable studies on human optics, human cone receptors and color vision and for the application of Adaptive Optics to the human retina</td>
<td>Friedenwald Award The Association for Research in Vision and Ophthalmology (ARVO)</td>
<td>Announced May 2005, presentation May 2006</td>
</tr>
<tr>
<td>Michael Helmbrecht</td>
<td>Research will shape how we live and work in the future</td>
<td>MIT’s Technology Review. TR 100 Group for 2004</td>
<td>October 2004</td>
</tr>
<tr>
<td>Jungtae Rha</td>
<td>Outstanding presentation at ARVO Annual Meeting</td>
<td>2005 Travel ARVO Grant</td>
<td>May 2005</td>
</tr>
<tr>
<td>Yan Zhang</td>
<td>Outstanding presentation at ARVO Annual Meeting</td>
<td>2005 Travel ARVO Grant</td>
<td>May 2005</td>
</tr>
<tr>
<td>Frank Marchis</td>
<td>Merit Recognition</td>
<td>Chrentien Award AAS</td>
<td>March 2005</td>
</tr>
<tr>
<td>Christian Marois</td>
<td>Best PhD Thesis</td>
<td>Canadian Astronomy</td>
<td>2004</td>
</tr>
<tr>
<td>Lynne Raschke</td>
<td>Merit Recognition</td>
<td>University of California Dissertation Year Fellowship</td>
<td>2004-2005</td>
</tr>
<tr>
<td>Claire Max and Lisa Hunter</td>
<td>Merit Recognition</td>
<td>Partnership Award, Hartnell College, Salinas CA</td>
<td>May 13, 2005</td>
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</tbody>
</table>
8.4. Undergraduate, M.S. and Ph.D. students who graduated during the reporting period, with placements

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Degree(s)</th>
<th>Years to Degree</th>
<th>Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Andrew Sheinis</td>
<td>Posdoc</td>
<td></td>
<td>Assistant Professor, U of Wisconsin</td>
</tr>
<tr>
<td>2  Antonin Bouchez</td>
<td>Postdoc</td>
<td></td>
<td>AO engineer at the California Institute of Technology</td>
</tr>
<tr>
<td>3  Marcos van Dam</td>
<td>Postdoc</td>
<td></td>
<td>Staff Researcher at Keck Observatory</td>
</tr>
<tr>
<td>4  Angelle Tanner</td>
<td>PhD 2004</td>
<td>7</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>5  Gaspard Duchene</td>
<td>Postdoc</td>
<td></td>
<td>CNAP Permanent Position Grenoble France</td>
</tr>
<tr>
<td>6  Caer McCabe</td>
<td>PhD 2004</td>
<td>6</td>
<td>NRC Postdoc at Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>7  Remi Soummer</td>
<td>Postdoc</td>
<td></td>
<td>NASA Postdoc at AMNH</td>
</tr>
<tr>
<td>8  Staci Choi</td>
<td>Postdoc</td>
<td></td>
<td>UC Berkeley</td>
</tr>
<tr>
<td>9  Karen Hampson</td>
<td>Postdoc</td>
<td></td>
<td>Postdoc in UK</td>
</tr>
<tr>
<td>10 Fan Zhou</td>
<td>PhD</td>
<td>5</td>
<td>Researcher at Alcon, Inc in Texas</td>
</tr>
<tr>
<td>11 Krishnakumar Venkateswaran</td>
<td>Postdoc</td>
<td></td>
<td>Senior Optical Scientist at Alcon, Inc in Florida</td>
</tr>
</tbody>
</table>

8.5. Outputs of knowledge transfer activities since the last reporting period

<table>
<thead>
<tr>
<th>Patent Name and Inventors/Authors</th>
<th>Number</th>
<th>Application Date</th>
<th>Receipt Date (leave empty if pending)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patent Name and Inventors/Authors</td>
<td>Number</td>
<td>Application Date</td>
<td>Receipt Date (leave empty if pending)</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------</td>
<td>-----------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>6 Method and Apparatus for Using Adaptive Optics in a Scanning Laser Ophthalmoscope. A. Roorda</td>
<td>6,890,076</td>
<td>May 10, 2005</td>
<td></td>
</tr>
<tr>
<td>Patent Name and Inventors/Authors</td>
<td>Number</td>
<td>Application Date</td>
<td>Receipt Date (leave empty if pending)</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>--------</td>
<td>------------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>11 A PZT unimorph based, high stroke MEMS deformable mirror with continuous membrane and method of making the same. E. H. Yang</td>
<td>CIT.PAU.14. PCT</td>
<td>6/12/02</td>
<td></td>
</tr>
<tr>
<td>12 Adaptive Optics Phoropter. Scot Olivier, Brian Bauman, Steve Jones, Don Gavel, Abdul Awwal, Stephen Eisenbies, Steven Haney</td>
<td></td>
<td>October 4, 2002</td>
<td></td>
</tr>
<tr>
<td>13 Repeatable Mount for MEMS Mirror System. Stephen Eisenbies, Steven Haney,</td>
<td></td>
<td>October 4, 2002</td>
<td></td>
</tr>
<tr>
<td>14A Method and Apparatus for an Actuator Having an Intermediate Frame, M. Helmbrecht, Clifford Knollenberg</td>
<td>11/097053 10/705,213 Continuance</td>
<td>April 20005</td>
<td></td>
</tr>
<tr>
<td>14C Method and Apparatus for an Actuator System Having Buried Interconnect Lines, M. Helmbrecht, Clifford Knollenberg</td>
<td>11/097599 10/705,213 Continuance</td>
<td>April 2005</td>
<td></td>
</tr>
<tr>
<td>15 Deformable Mirror Method and Apparatus Including Bimorph Flexures and Integrated Drive M. Helmbrecht</td>
<td>10/703,391</td>
<td>November 2003</td>
<td></td>
</tr>
<tr>
<td>15A Method and Apparatus for an Actuator System with</td>
<td>11/097777 10/703,391</td>
<td>April 2005</td>
<td></td>
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<tr>
<td>Patent Name and Inventors/Authors</td>
<td>Number</td>
<td>Application Date</td>
<td>Receipt Date (leave empty if pending)</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>--------</td>
<td>------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Integrated Control M. Helmbrecht</td>
<td>Continuance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Application of map-seeking algorithm to motion estimation, image dewarping and stabilization, D. Arathorn</td>
<td>Provisional Application No. 60/578,383</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name of Start-Up Company</th>
<th>Main Product(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Iris AO, Berkeley, CA</td>
<td>MEMS digital-mirror arrays for adaptive optics</td>
</tr>
</tbody>
</table>

8.6. Outputs of Knowledge Transfer Activities made during the reporting period not listed above.

Bruce Macintosh – Lawrence Livermore National Laboratory
Poyneer and Macintosh spatially-filtered WFS concept is being applied to high-power laser applications at LLNL.

David Le Mignant – Keck Observatory
Many technical aspects and details of LGS operations and LGS science operations have been made available to the community through our web page: http://www2.keck.hawaii.edu/optics/lgsao/

Brent Ellerbroek – California Institute of Technology
Periodic updates to an AO simulation code (CIBOLA) have been uploaded to the CfAO website.

Anand Sivaramakrishnan reviewed “ESO Very Large Telescope - Phase A Studies” in December 2004.
### 8.7. Summary listing of all of the Center’s research, education, knowledge transfer and other institutional activities

<table>
<thead>
<tr>
<th>Organization Name</th>
<th>Organization Type*</th>
<th>Address</th>
<th>Contact Name</th>
<th>Type of Partner**</th>
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<tr>
<td>Maui Economic Development Board (MEDB)</td>
<td>Non-profit</td>
<td>590 Lipoa Parkway, Suite #103, Kihei, Hawaii 96753</td>
<td>Leslie Wilkins or Jeanne Skog</td>
<td>Education/Diversity</td>
<td>Y</td>
</tr>
<tr>
<td>Air Force Maui Optical and Super-computing Site (AMOS)</td>
<td>Military</td>
<td>590 Lipoa Parkway, Suite 103, Kihei, Hawaii 96753</td>
<td>Joe Janni</td>
<td>Education</td>
<td>Y</td>
</tr>
<tr>
<td>Maui Community College</td>
<td>Academic</td>
<td>310 Kaahumanu Kailua, HI 96732</td>
<td>Mark Hoffman or John Pye</td>
<td>Education/Diversity</td>
<td>Y</td>
</tr>
<tr>
<td>Hartnell Community College</td>
<td>Academic</td>
<td>156 Homestead Ave, Salinas, Ca 93901</td>
<td>Charlene Frontiera</td>
<td>Education/Diversity</td>
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<tr>
<td>Boeing – Maui</td>
<td>Company</td>
<td>535 Lipoa Pkwy, Ste 200, Kihei, Maui, HI 96753</td>
<td>Lewis Roberts</td>
<td>Education/Research</td>
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</tr>
<tr>
<td>Oceanit - Maui</td>
<td>Company</td>
<td>MRTC, Suite 264, 590 Lipoa Parkway, Kihei, Maui, HI 96753</td>
<td>Curt Leonard</td>
<td>Education</td>
<td>N</td>
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<tr>
<td>Akimeka - Maui</td>
<td>Company</td>
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<td>Andrew Vliet</td>
<td>Education</td>
<td>N</td>
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<tr>
<td>Textron - Maui</td>
<td>Company</td>
<td>MRTC, Suite 222, 590 Lipoa Parkway, Kihei, Maui, HI 96753</td>
<td>Allen Hunter</td>
<td>Education</td>
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<tr>
<td>Maui High Performance Computing Center (MHPCC)</td>
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<td>550 Lipoa Parkway, Kihei, Maui, HI 96753</td>
<td>Gene Bal</td>
<td>Education</td>
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<tr>
<td>Institute for Astronomy</td>
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<td>PO Box 0209, Kula, HI 96790</td>
<td>Mike Maberry</td>
<td>Education</td>
<td>N</td>
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<tr>
<td>Textron - Maui</td>
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<td>Michael Reilly</td>
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<tr>
<td>Smithsonian Submillimeter Array (SMA)</td>
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<td>Billie Chitwood</td>
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<tr>
<td>Exploratorium</td>
<td>Science Center</td>
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<td>Barry Kluger-Bell</td>
<td>Education</td>
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<td>Keck Observatory</td>
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<td>Fred Chaffe</td>
<td>Education/Research</td>
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<tr>
<td>15 Gemini Observatory</td>
<td>Observatory</td>
<td>670 N. A'ohoku Place Hilo, Hawaii, 96720</td>
<td>Peter Michaud</td>
<td>Education/Research</td>
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<tr>
<td>16 Hispanic Associate for Colleges and Universities (HACU)</td>
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<td>8415 Datapoint Drive, Suite 400 San Antonio, TX 78229</td>
<td>Tony Leiva</td>
<td>Education/Diversity</td>
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<tr>
<td>17 University of Hawaii – Hilo</td>
<td>Academic</td>
<td>200 W. Kawili St. Hilo, HI 96720-4091</td>
<td>Richard Crowe</td>
<td>Education/Diversity</td>
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<tr>
<td>18 Watsonville High School</td>
<td>Academic</td>
<td>250 E. Beach St Watsonville, CA 95076</td>
<td>Gary Martindale</td>
<td>Education/Diversity</td>
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<tr>
<td>19 Center for Informal Learning and Schools (CILS)</td>
<td>Academic</td>
<td>3601 Lyon Street San Francisco, CA 94123</td>
<td>Candice Brown</td>
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<tr>
<td>20 ALU LIKE</td>
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<td>458 Keawe Street Honolulu, HI 96813</td>
<td>Doug Knight</td>
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<tr>
<td>21 Educational Partnership Center</td>
<td>Academic</td>
<td>U.C. Santa Cruz 3004 Mission Street, Suite 220 Santa Cruz, CA 95060</td>
<td>Carrol Moran</td>
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<tr>
<td>22 Carl Zeiss-Meditec</td>
<td>Company</td>
<td>5160 Hacienda Dve. Dublin, CA 94568</td>
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<td>Research</td>
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<tr>
<td>23 Northrop Grumman - Maui</td>
<td>Corporation</td>
<td>P.O. Box 398 Makawao, HI 96768</td>
<td>Albert Esquibel</td>
<td>Education</td>
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<td>24 Lucent Technologies</td>
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<td>Bell Labs. Murray Hill N.J</td>
<td>David Bishop</td>
<td>R &amp; D</td>
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<tr>
<td>25 Intellite</td>
<td>Company</td>
<td>1717 Louisiana, Suite 202 NE Albuquerque NM 87110</td>
<td>Dennis Mansell</td>
<td>R &amp; D</td>
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<tr>
<td>26 Ciba Vision Corporation</td>
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<td>11460 Johns Creek Parkway Duluth Georgia 30097</td>
<td></td>
<td>R &amp; D</td>
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<tr>
<td>27 Coherent Technologies Inc.</td>
<td>Laser Company</td>
<td>135 South Taylor Ave. Louisville, CO 80027</td>
<td>Tim Carrig</td>
<td>R &amp; D</td>
<td>Y</td>
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<tr>
<td>28 Wavefront Sciences</td>
<td>Company</td>
<td>14810 Central Ave, Albuquerque NM 87123</td>
<td>Tim Turner</td>
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<td>29 Bausch &amp; Lomb</td>
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<td>30 MEMX</td>
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<td>1368 Bordeaux Drive Sunnyvale CA 94089</td>
<td>Jim Koonmen</td>
<td>R &amp; D</td>
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<td>31 Lockheed ATC</td>
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<td>32 Pacific Disaster Center</td>
<td>Agency</td>
<td>590 Lipoa Parkway, Suite 259, Kihei, HI 96753</td>
<td>Sharon Mielbrecht</td>
<td>Education</td>
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<td>33 Maui Scientific Research Center</td>
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<td>590 Lipoa Parkway, Suite 272 Kihei, Hi 96753</td>
<td>Stuart Jeffries</td>
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**8.8. Summary Table**

<table>
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<tr>
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<th>the number of participating institutions (all academic institutions that participate in activities at the Center)</th>
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<td>2</td>
<td>The number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center)</td>
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<td>3</td>
<td>The total leveraged support (sum of funding for the Center from all sources other than NSF-STC)</td>
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<td>4</td>
<td>the number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF). Please EXCLUDE affiliates (click for definition)</td>
<td>256</td>
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8.9. Media Publicity the Center Received

   An educational partnership between the Center for Adaptive Optics (CfAO) at UCSC and Hartnell College in Salinas is bringing advanced astronomy courses to Hartnell students and encouraging underrepresented students to pursue degrees in science and engineering. In a ceremony on May 13 at UCSC, Hartnell president Edward Valeau presented the President's Partnership of Excellence Award to CfAO director Claire Max. Hartnell's collaboration with the CfAO is funded by the NASA Curriculum Improvement Partnership Award (CIPA) program. When the NASA-CIPA program evaluated its grant recipients recently, Hartnell was the top performing institution and received a perfect score, Valeau said.

2. UCSC lab shines light on stars
   By JONDI GUMZ Sentinel (Santa Cruz) staff writer May 18, 2005
   Claire Max, a professor of astronomy and astrophysics at UC Santa Cruz, is used to commuting to the Lawrence Livermore National Lab to do research on new high-tech tools to look at the stars. But now that UCSC has a cutting-edge laboratory of its own, she can spend more time on research instead of on the road. And UCSC students and faculty have opportunities to get involved in developing the next generation of astronomical instruments to help people better understand the universe. Scientists and administrators gathered Tuesday to celebrate UCSC’s new lab, funded in 2002 with a $9 million grant from the Gordon and Betty Moore Foundation.

3. Imke de Pater, Press releases:
   c. Press release on Uranus: Pictures of Uranus give the Best View from the Ground: http://www2.keck.hawaii.edu/news/index.php
      http://www.berkeley.edu/news/media/releases/2005/01/14; huygens2.shtml

9. Indirect/Other Impacts (Optional Section)

Please use this space to describe other outputs, impacts, or influences related to the Center’s progress and achievement during the current reporting period that may not have been captured in another section of the report. This section is optional.
10. BUDGET:

10.1. Y6 Budget and Expenses

Y7 Budget and Y6 Expenses have been forwarded to the NSF
11. ATTACHMENTS

Appendix A: Biographical Information of New Faculty
Appendix B: Organizational Chart (following pages)
Appendix C: External Advisory Committees (following pages)
11.1. Appendix A: Biographical Information of New Faculty
Biographical Information on New faculty has been provided to the NSF

11.2. Appendix B: Center Organizational Chart
11.3. Appendix C: Minutes of Advisory Committee Meetings

11.3.1. Report of the External Advisory Board

Center for Adaptive Optics
December 28, 2004

Executive Summary
The External Advisory Board (EAB) met at the Center for Adaptive Optics (CfAO) retreat held on 11-14 November 2004 at the UCLA Lake Arrowhead conference facility in the mountain east of Los Angeles. This was the first time the EAB met in coincidence with the CfAO retreat.

The EAB met with the CfAO leadership to hear reports on the Center activities, issues and long-range plans. Director Jerry Nelson, Director elect Claire Max, Chris DeMatrie, Lisa Hunter, Scot Olivier, and David Williams presented an overview of the CfAO program, opportunities and issues, and the activities and progress in each of the theme areas. The presentations were accompanied by extensive discussion of issues and plans for the future of the Center.

Director of the CfAO, Professor Jerry Nelson, announced his intention to step down as director of CfAO to assume new responsibilities as Chief Scientist of the Thirty Meter Telescope (TMT) project. Professor Claire Max will assume responsibilities as Director of the CfAO. The EAB members acknowledged this announcement with congratulations and a round of applause for incoming director Claire Max.

The field of Adaptive Optics is growing rapidly and is of critical importance to the current generation of 8 – 10 meter telescopes and to future telescopes such as the proposed thirty-meter telescope. The EAB recommends that the CfAO take the lead in approaching the new institution, the Adaptive Optics Development Program (AODP), to find ways coordinate activities and to develop a roadmap that supports AO in the broad astronomy community.

The Thirty Meter Telescope (TMT) project and the CfAO are evolving rapidly and there is significant overlap in personnel. The EAB recommends that the CfAO articulate clearly its role in the future of AO for both the TMT and for astronomy.

The EAB recognizes that there is value for the CfAO to support a “lab on the sky for testing new AO concepts”. The EAB recommends continued and increased use of AFRL’s AEOS facility on Maui for sky testing of Extreme Adaptive Optics (ExAO) components and subsystems developed by CfAO.

The Education and Human Resources theme led by Lisa Hunter is exceptional. The EAB recommends that the CfAO plan early and develop a strategy for continued support of this very successful education and outreach program.

Introduction
The External Advisory Board (EAB) met at the Center for Adaptive Optics (CfAO) retreat held on 11-14 November 2004 at the UCLA Lake Arrowhead conference facility in the mountain east of Los Angeles. This was the first time the EAB met in coincidence with the CfAO retreat. A goal was to have the EAB members take part in the scientific discussion and to learn first hand about the theme areas of the CfAO including theme 1, Education and Human Resources.
Members of the EAB who were able to attend the retreat wish to express their appreciation to the staff of CfAO who assisted with the logistics and arrangements that enabled the EAB to meet at the retreat.

The members of the EAB consist of international experts from academia and from education and industry. The current members of the EAB are Robert Byer (chair), Stanford University; Pablo Artal, U. de Murcia, Spain; David Burgess, Boston College; Tom Cornsweet, Visual Pathways Inc. AZ; Christopher Dainty, Imperial College, London; Robert Fugate, AFRL; Fiona Goodchild, UC Santa Barbara; Norbert Hubin, ESO; and Sidney Wolff, NOAO.

The External Advisory Board of the Center for Adaptive Optics reports to Robert Miller, Vice Chancellor for Research, Graduate Division, 477 Clark Kerr Hall, Santa Cruz, CA 95064, email rcmiller@ucsc.edu. The EAB reviews policies, priorities and management effectiveness of the Center. The EAB advises the Center on general strategy and long term planning. The EAB meets annually, prepares a report of its findings and recommendations and reports its findings to the Vice Chancellor for Research and to leadership of the Center for Adaptive Optics.

The EAB last met early in year on February 12, 2004 at the University of California Santa Cruz campus and in the new building on the UCSC campus. That meeting provided the EAB the opportunity to hear a full report on the activities of the Center for Adaptive Optics and the plans for each of the Theme areas. The EAB meeting was followed by a report prepared by the EAB chair, Professor Chris Dainty (Report of the External Advisory Board, May 2004). At that review, the EAB discussed the pros and cons of meeting at the CfAO fall retreat to take advantage of the scientific discussions and to learn first hand about the Theme 1 Education and Human Resources activities. The EAB elected to schedule its next meeting at the planned 2004 Fall retreat of the CfAO that was held on 11-14 November 2004 at the UCLA Lake Arrowhead facility in Southern California.

Following the meeting at the retreat held in November 2004, and as part of its verbal report to the CfAO, the EAB stated its preference to hold its annual meeting at the Center Fall Retreat in the future if possible. The advantages of full and open interactions with the participants of the retreat outweighed some of the disadvantages of the very tight scheduled opportunities for EAB discussions with CfAO leadership. Attention to the EAB meeting schedule at future retreats should allow adequate time to discuss the Center directions, future plans and issues.

The EAB met at the fall retreat on Saturday evening with the CfAO leadership to hear reports on the Center activities, issues and long range plans. Director Jerry Nelson, Director elect Claire Max, Chris Le Maistre, Lisa Hunter, Scot Olivier, and David Williams presented an overview of the CfAO program, opportunities and issues, and the activities and progress in each of the theme areas. The presentations were accompanied by extensive discussion of issues and plans for the future of the Center.

The EAB met as a board on Sunday morning and discussed the CfAO management and long range planning issues, the thematic activities and issues, and the structure and organization of the EAB meeting at the Fall Retreat. The EAB developed findings and recommendations at this executive session. The EAB reported its findings and recommendations to the CfAO leadership at a working lunch on Sunday noon. The EAB is very positive about the activities of the Center. The EAB congratulated the Director elect, Professor Claire Max, on her appointment as Center Director. Director Jerry Nelson had announced to the Fall Retreat the previous evening his intention to step down as the Director of the Center for Adaptive Optics to take new responsibilities as the Chief Scientist of the Thirty Meter Telescope (TMT) project.
The transition of the CfAO leadership and issues related to the evolution of the CfAO interactions with the TMT project were discussed. Also discussed were issues of the relation of CfAO to the development of AO technology for existing telescopes, and the strategy for the future of the CfAO as it enters and then completes the final five years as a Center under the NSF support.

The CfAO was reviewed at an NSF Site Visit on 26-29 September 2004. The report of the Site Visit committee identified and recommended action for the CfAO that stressed the need to develop an exit strategy during the five remaining years under NSF support. The Site visiting committee also noted that the CfAO has roadmaps for three of its four themes but must develop and roadmap for AO on extremely large telescopes and subsequently maintain this roadmap as AO technologies and approaches evolve.

The Site Visit review and observations and recommendation are captured in the Site Visit Report to the NSF about the elements of the CfAO program. (The Site Visit Report, Center for Adaptive Optics, University of California at Santa Cruz, September 26-29, 2004).

The Site Visit Report raised important issues regarding the future of the CfAO including the need to develop an exit strategy, the need to evolve roadmaps for key aspects of the technology programs, and the need to identify and act on key issues related to the rapidly developing Thirty Meter Telescope project and its implications for the CfAO. The discussion of these issues was an important aspect of the EAB deliberations. The highlights of the EAB discussions, and in some cases, recommendations, are presented in this report.

Mission
The purpose of the CfAO is to advance and disseminate the technology of adaptive optics in service to science, health care, industry, and education with the goal to be recognized as the leader in adaptive optics. The CfAO continues to contribute to the development and application of adaptive optics with an emphasis on science and astronomy, health care, and education and outreach. The rapid growth of the field of Adaptive Optics has led to competing centers and activities. This natural evolution will challenge the CfAO to focus and leverage its resources to remain a leader in the field.

Management Issues
Director of the CfAO, Jerry Nelson, presented to the EAB an overview of the Center and the issues of central concern. The issues presented and discussed included the leadership change with Jerry Nelson moving to assume responsibilities in the Thirty Meter Telescope project and Claire Max stepping up as the incoming Director of the CfAO. The expectation is that the overall management structure of the Center would remain the same. The second area of concern was the planning for life after the NSF support ends within five years. The key assumptions are that the research support will remain but in the hands of the PIs and that many of the CfAO key strengths will be carried forward as elements of the Center. One concern is to identify sources of funding for key activities of the Center. Another concern is to clarify the role of the CfAO in the broader arena of Adaptive Optics. For example, is the CfAO to be a Center for AO for the astronomy community or is the Center to focus on AO for the TMT? A third concern is the role of the CfAO within the University environment and the availability of space for both the Center and separate but nearby on campus Laboratory for Adaptive Optics.

Following a presentation of the issues faced by the Center, Director Jerry Nelson introduced the Highlights of each of the five theme areas. The theme leaders then discussed in more detail the status and future plans of each theme. The thematic issues are described briefly below.
The remainder of this section summarizes the discussion and considerations of issues of general concern to the future of the CfAO.

The field of Adaptive Optics is important to the future of astronomy especially to the current generation of 8 to 10 meter telescopes and to the future telescopes such as the proposed 30 meter Telescope (TMT). A new organization has emerged in the Adaptive Optics arena, the Adaptive Optics Development Program, AODP. The EAB recommends that the CfAO take the lead in approaching the AODP to find ways to gain synergy in R&D planning for AO. Coordination with AODP will be important for developing a roadmap that extends beyond CfAO and supports AO in the astronomy community broadly defined.

The Laboratory for Adaptive Optics, LAO, established on the Santa Cruz campus adjacent to the CfAO building, is important for the development and testing of new ideas and approaches to AO. The availability of the Laboratory is a key part of transferring adaptive optics concepts and subsystems into operating systems and in reducing the risks of implementing AO in modern telescopes. There are significant advantages in having the Laboratory for Adaptive Optics close to the Center. The EAB recommends that the CfAO Extremely Large Telescope (ELT) and ExAO road map be constructed in close collaboration with AODP, the LAO, the TMT Project office, the second generation Keck AO and, if possible, the GMT Project Office. The CfAO should be aware of technology developments in the Department of Defense (DoD) as part of this process. Proper coordination requires considerable effort but demonstrates CfAO leadership in the AO community and will result in benefits for all involved.

The Center activities, to this point, focus on R&D and developing new concepts for AO as applied to astronomy and vision science. The EAB recognizes that there is value for the Center to support a “lab on the sky for testing new AO concepts.” Collaboration and coordination with the AODP is important for optimizing the investment in new concepts for AO as applied to astronomy and for developing a roadmap for testing AO concepts on the sky. The EAB recommends continued and increased use of the AFRL’s AEOS facility on Maui for sky testing of ExAO components and subsystems developed by CfAO. This facility is not an 8 – 10 meter telescope, but it could provide significant risk reduction and concept validation with on-sky tests as an intermediate step between laboratory test-beds and final ExAO system designs.

The roles of the TMT and the CfAO are evolving rapidly. Questions were raised about the fraction of the CfAO program that will support the TMT as compared to AO for astronomy in general. The EAB recommends that the CfAO clarify its role with regard to support for AO development for the TMT and for astronomy in general.

**Thematic Issues**

**Theme 1: Education and Human Resources**

The Education and outreach program has been very successful and is expected to continue for the next five years. The EHR program of CfAO has been recognized nationally as a innovative leader in developing programs to broaden the participation in science and is to be commended. The program in Hawaii is novel, well developed, and should remain of high priority. The EAB continues to support the present focus of activities by the EHR program. Because of these successes, there is concern regarding support beyond the five-year horizon defined by the NSF. The EAB recommends that the CfAO plan early and develop a strategy for continued support of the very successful education and outreach program. The program has demonstrated effective ways to extend outreach to the community on Maui. The EAB recommends that the success of these programs be published in peer-reviewed journals so that the key elements can be captured.
and utilized by others in the future. The publications should also provide a summary of outcomes of the programs developed by the Center.

The connectivity of the research areas of the Center can be improved by providing mobility for graduate students and for postdoctoral scholars. The EAB recommends that the Center explore methods to improve the mobility of students, perhaps for periods of up to six months, across research areas of the Center.

Education and career development is important for graduate students involved with the broader programs of the Center. The tradition is that the thesis mentor provides career advice for graduate students. The EAB suggests that the Center may need to pay more attention to the mentoring of graduate students that participate in the research programs of the Center.

Theme 2: AO for Extremely Large Telescopes
The giant telescopes, for example the thirty-meter telescope, are becoming a reality. These next generation telescopes require AO built into the design from the inception. For the TMT, 7 of 8 members of the AO working group are CfAO members. The large overlap with the TMT places a special emphasis on planning for the CfAO role in the future. The CfAO must work with the TMT to define roles and responsibilities that in the future would form the basis for a roadmap for both the TMT and for the CfAO. The NSF has requested a roadmap be prepared by February 2005. The roadmap should be considered a work in progress as at this time as it is very early in the history of the TMT to expect a detailed plan for the incorporation of AO into the design of the TMT.

One goal suggested for the Center is to develop a point design for the thirty-meter telescope. The development of all of the technology components for the AO system is beyond the resources available to the Center. Thus the Center must find appropriate partners for the development of component technologies for AO. The technologies and approaches for AO for the TMT can be demonstrated at a laboratory level to reduce the risks prior to taking the concept to a demonstration on a large telescope. The Laboratory for Adaptive Optics at Santa Cruz can provide the testing of component systems to qualify vendors prior to submitting cost proposals.

The Center has made good progress in the development of components of the AO system. The question that needs attention is the role of the CfAO for the construction and testing of an ExAO system on an existing 8 to 10 meter class telescope. The undertaking of a system development and testing at a telescope is a major step that is beyond the current capabilities of the Center. In this regard, the limited resources of the CfAO will force the Center to set priorities. Simply stated, are the priorities for the Center in the development of AO capabilities to focus on concepts and advanced technologies for AO, or on AO systems developed for on sky testing at Keck or perhaps Gemini? If the step to develop, deliver and to test an AO systems at these astronomical facilities is not practical for the Center, is an alternative to consider testing advanced AO capability at the Maui facility in partnership with the Air Force?

The limited resources of the CfAO means that the Center must work to identify and prioritize key technologies that need to be developed for AO. The development of an appropriate laser for the sodium yellow laser guide star is an example. Establishing a set of top-level requirements for the sodium yellow laser source would be helpful as a guide for the technical development of a laser source.
Theme 3: Extreme AO

Extreme AO is critical for enabling the capabilities of proposed next generation extremely large telescopes. The use of Extreme AO to enable high contrast astronomy is also an important research objective.

One possibility, as a first step, is the development of ExAO for telescopes in the 8 to 10 meter class. The challenge for the CfAO is the cost and time to prepare a proposal for instrument development and installation and testing on a current telescope. The experience and the mission of CfAO, to date, has been the support of research on advanced AO and the study and testing of AO subsystems to enable AO in the future. It is not evident that the CfAO has the resources and the talent to undertake the construction, delivery and on sky testing of ExAO system on an existing astronomical telescope. A project of this magnitude would certainly take the attention of a large fraction of the human resources of the CfAO. It would move focus of the CfAO activity from research on advanced AO technologies and AO systems to the immediate and pressing need to deliver a system on time and to cost to an existing 8 – 10 meter telescope.

The need to develop advanced AO systems and to demonstrate system performance on existing telescopes is an important step prior to taking ExAO to the TMT. However, limited CfAO resources suggests that partnerships are essential for this undertaking. In this sense, the use of the Air Force Maui facility as a test site for extreme AO may have advantages if an alternative astronomical telescope is not available.

Theme 4: Vision Science

The partnership of AO in astronomy and AO for vision science is a positive contribution by the Center. Both communities are informed by the similarities and differences of AO as applied to vision science and to astronomy. The incorporation of Vision Science as a Theme of the CfAO is a key success for the Center. The application of de-convolution methods for image analysis as developed for astronomical images, for example, is a windfall when applied to vision science. This is but one example of the cross fertilization recognized by Charles Townes when he stated that it was useful to go across fields to learn things that inform your research.

The EAB recognizes that the CfAO has taken a bold step to bring AO technology to vision science as well as to astronomy. The challenges of adaptive optics to each research area informs the other and helps to bring AO to technical reality in both.

Theme 5: Knowledge Transfer

The Center has developed an effective model of technology transfer. Knowledge transfer is a “body contact sport” that is best accomplished by the movement of people, especially graduates and postdoctoral scholars from the Center to industry. The EAB suggests that the CfAO look closely at sponsoring postdoctoral scholars with US citizenship to work at the Star Fire Optical Range, SOR, or perhaps at Maui, on specific projects allow better transfer of technology developments and knowledge between the AFRL and CfAO to the potential benefit to both organizations.

The Affiliates program is centered on vision science as might be expected. The growth of the Affiliates program, from 11 member companies at present to many more in the future may provide resources to help the Center make the transition to life after the NSF. Future growth of the Affiliates Program may require the attention and leadership of a Executive Director to expand and to form lasting partnerships with affiliated companies. The Center should consider establishing the Executive Director position when appropriate to assist with the growth of the Affiliates program as one element of the transition of the Center to life after the NSF.
The Program Advisory Committee met June 2, 2005 with members of the CfAO executive committee. This report summarizes the PAC conclusions. Present were:

PAC: Mark Colavita, Michael Hart, Stanley Klein (chair), Carrol Moran, Malcolm Northcott and Rod Ogawa

CfAO: Claire Max, Jerry Nelson, Chris Le Maistre, Andrea Ghez (via videoconferencing), Lisa Hunter, Scot Olivier, David Williams and Austin Roorda

The meeting began with Claire Max giving an overview of the past year followed by detailed presentations of the four themes. There was a much larger than usual oversupply of funding requests, but the CfAO grant review that took place the days before the PAC meeting did a superb job of making the difficult decisions about getting the requests to balance with the available funds. The PAC supports those decisions with a few minor comments below. We were informed about Claire Max being appointed as the new CfAO director and Don Gavel taking the position of Associate Director of Theme 2. The PAC concur with the wisdom of this shift in governance, given Jerry Nelson's expanded role as director of the Thirty Meter Telescope project.

One of the most fascinating experiences of the day for two of us (Klein & Colavita) was a tour of the AO Laboratory. It is most impressive and we look forward to hearing more about its accomplishments as it gets rolling.

The most important item of concern to the PAC is not only the exit strategy for the next four years, but also what happens afterwards. We are especially concerned about planning for the post-NSF years for Themes 1 and 4. Themes 2 & 3 will have continuance at UCSC through the Thirty Meter Telescope project. We were pleased to hear of the planning workshop the first week of August on precisely this range of topics. We were provided with the document "Strategic Plan for Years 6-10, March 2005" that was developed in preparation for the August workshop. That document was well thought out for the next few years, however it didn't cover the post-NSF years. Given that the workshop is still in the future, little will be said about that important topic in the present report except for the following:

We strongly suggest that for the next three years a significant portion of the Theme 1 and 4 budget be devoted to projects that have a concrete plan for obtaining sustained post-NSF funding. We hope this new funding option would be discussed at the Half Moon Bay strategic planning retreat, at the other upcoming CfAO meetings, and in the call for future proposals. The PAC would like to get a report of the August Half Moon Bay workshop when it is available. We will look it over and may have comments afterwards.
Theme 1: Education

The PAC continues to be impressed with the educational work of the Center. The community of learners created among the graduate students as a result of the Professional Development Workshop forms the core of the Center community. It brings graduate students together across vision science and astronomy and across the campuses involved in the CfAO. The evolution of the PDW to include deeper levels of training and opportunities to play leadership roles in the PDW is impressive.

The PAC supports the recommendation of the review committees to continue to fund the PDW, the COSMOS work, and the internship program with short courses. The PAC is also in agreement to support the post-doc position to redesign the astronomy course and bring in the inquiry methods that have been encouraged through the PDW. The PAC is also in agreement that it is time to move in a new direction to provide documentation and evaluation of the education component of the CfAO.

The PAC recommends that those who have been involved in the development of the PDW and the short courses be supported to write up descriptions of what was involved in those activities. The suggestion that an extra day be added on to the strategic planning retreat to facilitate this might prove useful. Also funding a writer to take the individual pieces developed and weave them into a coherent whole might facilitate this documentation being completed. This documentation of the work should be a priority of the Education director in the coming year. The PAC also encourages the director to hire an outside evaluator and provide clear outcomes that would be measured in the PDW and in the short courses. It would be useful to know what the graduate students know about inquiry before the PDW, what strategies they employ in teaching pre PDW and then to see what knowledge and strategies are demonstrated post PDW. The same kind of outcome-based learning could be measured with the COSMOS students and in the short courses. The PAC further suggests that Doris Ash be encouraged to write up her research and at the least organize the database of video materials in ways that it can be mined for research purposes if not by Doris, by others.

The PAC agrees with the recommendation that the 286 course not be taught in Spring 2006 but rather that a committee be assigned to:

1) assess the campus climate and need for the course and determine if it might be an every-other-year course offering,
2) determine where the course should reside and
3) determine who should be encouraged to take the course.

The committee to assess this issue should be made up of representatives from CILS, CfAO, The Education Department and the division of Physical and Biological Sciences and graduate education. This group should be charged to explore the issue and make recommendations to the CfAO director by Spring 2006.
The PAC would further like to recommend that the UCSC astronomy department play a lead role in increasing the professional development offered to graduate students to improve their ability to teach by designing a course that all astronomy graduate students would be required to take prior to or during the first year of holding a T.A. position. This course would go beyond the current campus offerings for T.A. training to deal with issues of improved pedagogy. There is a great variety of methods for how such a course could operate. UC Berkeley requires that every graduate student T.A. take such a course before or during their T.A. position. For details, contact Linda von Hoene, the director of the UC Berkeley Graduate Student Instructor Teaching and Resource Center, (510) 6424456, vonhoene@berkeley.edu.

The PAC would also recommend that the strategic planning address ways to institutionalize the models developed by the CfAO like the PDW, the short courses and the internship training. The Education Director should explore opportunities to disseminate the model across the campus with other graduate students, across the state through the COSMOS, program and across other NSF projects around the country. The Education Director should also explore collaboration on new funding opportunities to institutionalize this work.

**Theme 2: AO for Extremely Large Telescopes**

We note the change in focus in this theme, based on the recent significant progress in lasers for ELTs and other factors. CfAO’s choices in this theme seem well thought out and appropriate given their available funding and timeline.

While a few years ago, lasers were a high risk, high payoff area, and highly appropriate for CfAO funding, with the recent availability of several lasers which are at least adequate, if not yet ideal for ELTs, CfAO decided to focus their resources in areas with less maturity. This has meant ending funding for one on-going laser program, and not starting work on improving pulse formats for another. For the former, CfAO may want to consider if there are any close-out activities that it should be involved in.

Theme 2 has increased their funding of MEMS. This is largely a judgment by CfAO that MEMS for AO may provide the type of “monument” that the center seeks, and that now is the time to bring the development to fruition. It’s an appropriate area for focus given that MEMS are ideal for application to vision science instrumentation in addition to astronomical use for small FOV applications (like extreme AO or multi-object AO for ELTs). With TMT’s withdrawal from the MEMS collaboration, CfAO must take up more of the direct burden. There is some risk focusing mostly on a single vendor for the near-term activity, but they do have best record to date, and this decision makes sense. However, it’s also appropriate that they have provided funding to a different approach for high stroke mirrors. This MEMS development activity should be watched carefully to ensure a good outcome over the last few years of the center.

We support the continued support on laser guide star science to get more papers out, as well as on PSF and other modeling to enable optimal use of the existing systems.
The 2X oversubscription of proposals to this area required a difficult ranking process, which impacts some previously funded work. Given the long process involved in finding and hiring excellent postdocs, funding decisions should continue to recognize this impact in order to keep good postdocs in this field.

**Theme 3: Extreme Adaptive Optics.**

A narrow field of view, relevant to planet finding in Theme 3 is well matched to the MEMS direction of CfAO. The Tucson folks have adopted a MEMS approach for their planet finding interests. Coupling MEMS development with their experiments in closed-loop focal-plane wavefront sensing could lead to a demonstration of high contrast speckle suppression without the loss of light inherent in a coronagraph. This would further broaden the scope of CfAO’s legacy in hardware development.

The present Theme 3 plan is to go with the project to build an Extreme AO Planet-Finder instrument at the Gemini 8-m telescope if Gemini funding comes through. In parallel, the Theme 3 group is doing design studies for an instrument for the Thirty-Meter Telescope, which is farther away in time. Is there a possibility of an intermediate plan in which research could be done to tweak or add to the present AO to demonstrate the narrow field coronagraphic capability. While such an instrument would not provide all of the gains envisaged for the full instrument, it could help kindle wider interest from the astronomical community and to help prime the pump for further funding. We noted last year that one possible option for such a demonstration would be to remove the fixed speckle from the telescope optics to generate a much smoother long exposure PSF.

**Theme 4: Vision Science**

This theme has been very productive. We were pleased to hear of Don Miller's progress. The past uncertainty regarding MEMS mirrors seems to be clarifying somewhat with Boston MicroMachines producing usable mirrors and with further advances apparently forthcoming. The comments on MEMS in the Theme 2 discussion apply fully for the Vision Science direction. The PAC appreciated the synergy between Themes 2 and 4 on focusing on MEMS.

As stated above, the PAC is concerned that insufficient thought has been devoted to planning for post-NSF funding in Theme 4. The synergy of getting vision scientists with CfAO and Livermore has been dramatic in facilitating several large grants to be written and awarded. It would be good for this type of interaction to continue and to be broadened to include high-tech research areas other than adaptive optics. The infrastructure for maintaining and expanding these successful collaborative efforts needs
to be developed in the next few years. It is possible that the PAC will have an addendum to this report when we get information of what transpired at the strategic planning workshop in early August.

Sincerely,

The CfAO, Program Advisory Committee

Mark Colavita
Michael Hart
Stanley Klein (chair)
Carrol Moran
Malcolm Northcott
Rod Ogawa