Center for Adaptive Optics

Annual Report
August 1, 2004

Program Year 5
Reporting from November 1, 2003 to October 31, 2004

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1. GENERAL INFORMATION

1.1. General information on participating institutions:

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<tr>
<th>Date submitted</th>
<th>August 1 2004</th>
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<tr>
<td>Reporting period</td>
<td>November 1 2003 to Oct 31 2004</td>
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Names of participating institutions

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<tr>
<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>
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<td>Institution</td>
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<td>University of California, Los Angeles</td>
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<td>8</td>
<td>University of California at Irvine</td>
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<td>9</td>
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No new faculty at this stage. However as reported in Section 8.6 two postdocs have recently accepted faculty positions.

1.3 Executive Summary

In March 2001, the membership of the Center for Adaptive Optics (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 the report below, the efforts and accomplishments of the CfAO are largely organized by these themes.

On February 3rd 2003, the CfAO submitted to NSF a proposal for the continuance of funding in the years 6 to 10 (November 2004 to October 2009). The NSF site visit occurred on the campus of the University of California, Santa Cruz on April 15th to 17th 2003.

The site reviewers recommended that the Center’s funding be continued.
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.

1.2.2 Themes
The theme structure continues to positively impact the Center’s Education and Research programs. Center investigators are encouraged to develop collaborative programs inter and intra theme. 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:
1. Increasing the versatility of Center students and post-doctoral researchers.
2. Establishing a center-based model for retention and advancement of college-level students from under-represented groups:
3. Increasing the number of high school students from under-represented groups who are prepared to pursue a science/technology/mathematics degree in college:

The Education Theme was rated as excellent by the 2003 site visit committee.

**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. Developing an adequate adaptive optics system 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.
Effective Adaptive Optics on large mirror aperture (e.g. 30m) using laser beacons will require knowledge of the tomography of atmospheric turbulence. 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 above the telescope. In the last year CfAO scientists have developed a new paradigm for Adaptive Optics for ELTs. This requires determining the tomography of the atmosphere with laser guide stars (LGS), computing atmosphere corrections in set directions, and applying the computed corrections in those directions – open loop and over small fields. MEMS deformable mirrors are likely to be a technology of choice. The CfAO strategy has been to develop crucial concepts and components needed for successful implementation of AO on ELTs, recognizing that its implementation for a 30-m telescope requires resources from some other source.

CfAO researchers have proactively sought additional sources of funding, including the new Laboratory for Adaptive Optics at UC Santa Cruz which is a partner in the Theme 2 effort. CfAO members participated in NSF’s roadmap process for AO, culminating in the NSF AO national development program (AODP) at $2.5M per year for astronomical adaptive optics, and the Thirty Meter telescope (TMT) consortium consisting of AURA, ACURA, University of California and California Institute of Technology. The TMT consortium has a funding commitment of about $70 million over the next four years, with $10M directed at AO design and key component development.

**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 close to bright sources 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 effects can dramatically improve the achievable contrast ratio for astronomical observations. Specifically, the CfAO has undertaken a project to design an ExAO instrument for a current 8-10m telescope. The Laboratory for Adaptive Optics at UC Santa Cruz is a partner in these Design and simulation studies.

The CfAO had recognized the necessity for project management – also recommended by the NSF 2003 site review team, and has recruited a professional project manager for ExAO. Budgets and Gantt charts continue to be updated to clearly delineate sources of funding, schedules, and deliverables that can be achieved under varying credible funding scenarios. Gemini Observatories have identified the funds necessary for the building of the instrument and CfAO has been awarded a $200,000 feasibility study contract in 2004. If the CfAO approach is selected, $14 million will be provided to build the instrument.

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

Ophthalmic AO systems have been demonstrated in the laboratory for scientific research. The next horizon is to engineer compact, robust AO systems for use in clinics as well as scientific laboratories. The long-term goal is to commercialize a compact AO system for ophthalmic applications. Along the way, these new and existing AO systems are being
used to advance our understanding of human vision, and to explore medical applications of adaptive optics. This is a crucial way to provide feedback for the utility of the advanced ophthalmic AO designs.

1.2.3 Research Management

Conferences - The Center organizes annual Fall and Spring Research Retreats aimed at attendance by all researchers. In addition smaller workshops and symposia on specialized topics are held during the year as the need arises.

The Fall Retreat provides researchers the opportunity to share their results with colleagues while in Spring they are encouraged to plan future research and to develop collaborative projects. Shortly after the Spring retreat, researchers forward their proposals for continuing or new research. Each proposal is 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.

Scientific management - is provided by the Director, the Deputy 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’s 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 broad directions of the Center. It reports to a University oversight committee chaired by the Vice-Provost for Research at UCSC. The PAC also meets annually and assists in ensuring the scientific and technical vitality of the Center’s research program.

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 workshops and summer schools, report writing, etc.

1.2.4 Partnerships

The objective of CfAO’s partnership activities is to enhance the Center’s ability to fulfill both its research and education goals. The Center is pursuing this objective through:
1. Leveraging its efforts through industry partnerships and cross-disciplinary collaborations.
2. Stimulating further investment by government and industry sources in AO research and development
3. 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 on-going partnership activities with 13 optics and micro-electronics companies, 5 national laboratories, 5 non-CfAO universities, 6 astronomical observatories, and 2 international partner institutions. In March 2003, CfAO initiated an Industrial Affiliates Program, whereby companies pay a membership fee to participate at Retreats and stay abreast of emerging AO technologies. To date three companies have joined. 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.

As mentioned above, our vigorous support of an NSF roadmap for AO development in astronomy has paid off, with the recent NSF announcement of the multiyear AO development program (AODP). Researchers from the CfAO and Caltech are playing lead roles in the design studies and development of the Thirty Meter Telescope. The Gemini Observatory has funded two design studies for a high contrast coronograph for extrasolar planet detection. Each study provides $200K, with the goal of further funding of $14 million for the building of the coronograph. The ExAO theme is leading the effort in one of the two design studies.

1.2.5 Highlights for Year 5
1. **New Short Course in Hawaii.** The very successful CfAO Education Theme activities reported in year 4 have continued in Year 5. This year the Internship program associated in past years with students on the mainland and on Maui was successfully extended to the Big Island of Hawaii. As in Maui and the mainland, interns were prepared for their internships at the Observatories with an intensive one week Short Course – The Akamai Observatory Short Course (AOSC). It was collaboratively taught by CfAO and Observatory personnel drawn from the Big Island observatories. This new AOSC gives students background in astronomy, familiarity with jobs at astronomical observatories, and an understanding of the scientific method, through a set of inquiry-based activities supplemented by lectures and a tour of the observatories on the summit of Mauna Kea. The course includes a unit on the role of astronomy in Hawaiian culture.

2. **Interaction between Astronomers and Vision Scientists** continues to be strong. One recent example is the collaboration between vision scientists at the Universities of Rochester and Houston, and astronomer Julian Christou of UCSC. Christou applied deconvolution techniques previously used for astronomy to sharpen images of the human retina. Another good example of the type of cross-fertilization that is taking place was the visit by astronomer Marcos van Dam to the vision science laboratory of Don Miller at Indiana University. Van Dam visited Indiana on a mini-grant provided by the CfAO Education theme. While there, he identified and resolved several software problems that were limiting the use of the Indiana AO system.

3. **Extremely Large Telescopes.** In Theme 2, CfAO researchers have become proactive leaders within the extremely large telescope astronomy community, engaging in studies for almost all aspects of the Thirty Meter Telescope (TMT) design. Recent funding by the NSF Adaptive Optics Development Program, and by the Gordon and Betty Moore Foundation to Caltech and the University of California are a direct result of these efforts. CfAO researchers are continuing their active participation in all these programs, which supplement the CfAO research effort.

4. **Multi-Object Adaptive Optics.** During Year 5, CfAO members explored several different multiple-guide-star tomographic measurement and reconstruction methods. A very exciting direction is “multi-object AO” (MOAO) in which small MEMS-based AO systems are placed in the focal plane above each discrete object of interest (e.g. each distant galaxy), and the output of each AO system is sent via optical fibers to a spectrograph slit. The wavefront sensing and reconstruction would be done using open-loop tomography with multiple laser guide stars, and the optical correction needed in the direction of each galaxy would be applied to its own MEMS mirror. 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. For applications requiring an entire field of view to be corrected
by AO (rather than multiple discrete sub-regions), the CfAO has continued to explore
multi-conjugate AO (MCAO), in which multiple larger deformable mirrors are used,
each optically conjugate to a different height in the atmosphere.

The Chicago Sum Frequency Laser (CSFL) was delivered to Mt. Palomar Observatory
in May. The prototype laser achieved a power output of 3.5 watts in Jan 2004 and
maintained a power level above 2.5 watts for 3 days of continuous operation with
minimal operator intervention, and despite temperature fluctuations in the
room of 20 degrees. The laser uses no active loops and is inherently stable due
to a new cavity design. Figure 1 shows an image of the Chicago laser in operation.

**Figure 2.10** The Chicago sum-frequency laser in operation at the University of
Chicago, prior to being shipped to Mt. Palomar.

5. **Black hole at the Galactic Center.** In Year 5 CfAO astronomers discovered a variable
point source, imaged in the L band (wavelength 3.8 µm) with the Keck II 10 m
telescope's adaptive optics system, that is coincident to within 18 mas (1 σ) of the
Galaxy's central supermassive black hole and the unique central radio source Sgr A*.
This is the first infrared or optical imaging of the point source coincident with the
position of our Galaxy’s central black hole.

6. **Extreme Adaptive Optics.** In Theme 3, the CfAO is one of two teams currently
engaged in a design study for an Extreme Adaptive Optics instrument (in our case a
coronograph) for the Gemini Observatory. Gemini Observatory expects to fund the
building of at least one of these instruments in 2005 at a funding level of $14 million.

7. **Laboratory for Adaptive Optics.** Strong Progress has been made on the development
of the Moore Foundation funded “Laboratory for Adaptive Optics” at UCSC. Dr.
Donald Gavel has been appointed Director of the Laboratory, and the first phase of the
construction of the laboratory has been completed. Technical staff have been hired,
and research on both extreme adaptive optics and AO tomography for extremely large
telescopes is under way.

8. **Vision Science.** The AO phoropter developed by the Lawrence Livermore National
Laboratory has been “field tested” in the vision science laboratory at the University of
Rochester. Several improvements have been made to the instrument. The recent
replacement of the deformable mirror by one having a 2 µm stroke marks a
considerable step forward; the AO phoropter is now to be released to Bausch and
Lomb for further testing.
1.2.6 Closing remarks
In this fifth year of the CfAO there have been strong advances in its research agenda and vigorous collaborative efforts between members. We have been able to obtain additional sources of funding in the ELT and ExAO astronomy themes, as well as in Vision Science. This is an affirmation of the Center’s strategy to focus on critical AO components and concepts in order to catalyze the required levels of funding from other sources. Our Spring Retreat in April 2004 focused on strategic plans for the complete range of Center activities over the remaining 5-year life of the Center.
2. RESEARCH

2.1.1. Center’s Overall Research Objectives

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

The research objectives remained unaltered in Year 4. 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.

2.1.2. Performance and Management Indicators.

In their research proposals for Year 5, Principal Investigators (PI’s) identified 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) consisting of the Executive Committee reviews all renewal proposals and recommends funding levels to the Director.

2.1.3. Problems

The problems identified by the 2003 site visit team have been or are in the process of being resolved.

1. Inadequate funding for the ELT and ExAO themes. — Sources of additional funding have been identified for both the ELT and Extreme AO themes.
2. Inadequate communication of AO results to the Astronomy community. — At the time the CfAO had been diligent in communicating its research through membership on select committees, newsletters, the web etc. There was however, a paucity of research articles on AO results using Laser Guide Stars (LGS). The first of these articles was published by CfAO researchers in late 2003, and several more will be submitted in Year 5.
3. Perceived inadequate management controls in Theme 3 – A project manager has been appointed and relevant management control methods implemented.

Current problems that the CfAO is working on are:

1. Vision Science researchers are seeking ways to accelerate the availability of commercial instruments based on the technologies being developed by the CfAO.
2. While commercially available MEMS deformable mirrors have improved markedly in performance over the past year, they still do not meet a prime requirement of vision scientists, namely 10 micron stroke.
2.2. Research Thrust Areas

2.2.1. Theme 2: Adaptive Optics for Extremely Large Telescopes

2.2.1.1. Introduction

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.

The CfAO is focusing on four specific goals: 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 represent areas where the CfAO and its “center mode of operation” can make a unique contribution. The top level of the roadmap developed is shown in Figure 2.1.

2.2.1.2 Research Accomplishments and Future Plans

2.2.1.2.1 “Point design” for adaptive optics on a 30-m telescope: Analysis, Modeling, and Simulation

In multi-laser guide star tomographic wavefront reconstruction, multiple laser guide stars (or natural stars if available) are used as reference beacons (Figure 2.2). With multiple

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beacons, tomographic reconstruction of the atmosphere is possible: one can solve for the entire 3D structure of atmospheric turbulence above the telescope. 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 5, CfAO members explored several different multiple-guide-star tomographic measurement and reconstruction methods. An exciting direction is “multi-object AO” (MOAO) 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. For applications requiring an entire field of view to be corrected by AO (rather than multiple discrete sub-regions), the CfAO has continued to explore multi-conjugate AO (MCAO) methods in which multiple deformable mirrors are used, each 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. Currently there is a lack of accepted analytic models parameterizing key design issues, and detailed simulation codes cannot explore parameter space fast enough to provide all of the needed 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 5. 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 prioritizing of outstanding ELT AO design issues, four key "show-stopper" issues were identified:
1. Quantify the cone-effect when using multiple laser guide stars,
2. Mitigate laser guide star spot elongation,
3. Develop an optical design that gets the laser guide star light through the AO relay optics without severe aberration,
4. Optimize AO reconstruction and tomography algorithms for both MOAO and MCAO.

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Specific modeling tools under development in Year 4 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; and 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 being 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 main simulation and modeling codes to date. Arroyo, CIBOLA, and PAOLA (Performance of Adaptive Optics for Large Apertures, a set of functions and procedures written in IDL for calculating the performances 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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<th>Domain</th>
<th>Optica Propagation</th>
<th>Output</th>
<th>Goal: Speed or Accuracy</th>
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<tr>
<td>CIBOLA</td>
<td>Covariance Incorporation Basic Option for Linear Analysis</td>
<td>Fourier</td>
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<td>Fast $O(N \log N)$</td>
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<tr>
<td>TAOS</td>
<td>Tool for Adaptive Optics Simulation</td>
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<td>UNIX, supercomputer (ported to MHPCC)</td>
<td>Port to supercomputer</td>
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<tr>
<td>Arroyo</td>
<td>(Object Oriented Library for AO elements)</td>
<td>Spatial</td>
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<td>Validation suite of codes analytical model</td>
<td>UNIX</td>
<td>Input from ARCADIA</td>
</tr>
</tbody>
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Notes: *ARCADIA (Associated Reconstructor Computations Analytically Derived and Including Anisoplanatism)

2.2.1.2.2 Specific progress in analysis, modeling, and simulation in Year 5 is described below.

**MCAO/MOAO scaling laws:** These performance scaling laws are now established (with efficient computation) thanks largely to the adaptation of methods of A. Tokovinin to the 30 meter telescope case. Extension of the technique to spherical waves (see Figure 2.3) has allowed us to predict the “cone effect” caused by the sodium guide stars being at finite altitude. Ellerbroek’s CIBOLA code does rapid calculation of error budget terms and PSFs, accounting for guide star configurations, $C_n^2$ profile, and finite controller bandwidth.

**Spot elongation:** 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 J. Nelson are fabricating a prototype device under NSF’s Adaptive Optics Development Program. Options for pulse tracking via “dynamic refocus” are also
under consideration and may be tested in the lab. Ellerbroek has studied optimal centroiding algorithms for CW lasers via closed-loop simulations of 30-meter telescope MCAO systems.

**AO relay optics.** The aberration of the laser beam through the traditional concept MCAO relay optics is frighteningly large, because the 90 km focus is almost in the near field of the telescope. A large non-common path error offset would be needed to compensate for it. Alternative concept designs for AO are seriously being studied in which the laser guide star wavefront is sensed “open-loop” (that is, not reflecting off the deformable mirrors) with its own optical system, thus finessing the aberration problem; linear wavefront sensor design ideas pursued by Brian Bauman and Lisa Poyneer at LLNL are helping to address this problem. 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. The MO (multi-object) AO system feeds a spectrograph using multiple single-deformable mirror AO systems, one dedicated to each narrow field science object. Multi-conjugate AO (MCAO) uses several deformable mirror in series, and is specialized for wide field imaging. Both of these systems use a multiple laser beacon constellation to perform the tomography that provides wavefront control information.

**Fast Reconstructors.** We developed a fast wavefront reconstructor using an imbedding technique with conjugate gradient procedure. The imbedding technique converts an annular-aperture wavefront reconstruction problem into a square-aperture wavefront reconstruction problem. We call this fast wavefront reconstructor the recursive filtering algorithm. This technique allows fast transform methods to be used with the conjugate gradient or other iterative methods when the solution aperture is annular. We have already developed two fast methods to use with the recursive filtering algorithm to accelerate the iterative wavefront reconstruction. One is an O(N) method, which is about to be released.
and published. The other is an $O(N \log N)$ method, which uses a Hudgin filter combined with a regularization filter in the 2-D DCT domain in its imbedding step to solve the wavefront reconstruction under Fried geometry. The regularization filter takes account of the covariance information of the atmospheric turbulence. We have tested these fast wavefront reconstructors using Monte Carlo simulations for a single-conjugate adaptive optics system with up to 250,000 actuators. Over the past 1.5 years we have been developing a Matlab software package for rapid prototyping of fast wavefront reconstructor and tomography algorithms. We have proposed a three-step algorithm for MCAO wavefront reconstruction, a variant of the minimum-variance algorithm developed by Ellerbroek. In this algorithm, we separate the estimation step of the algorithm of Ellerbroek into two steps, so we obtain a three-step implementation of the minimum-variance method in a suboptimal sense. Our algorithm consists of a fast wavefront reconstructor, layer-strength weighted backprojection, and the fitting step which is basically the same as in the second step of the minimum-variance method. Therefore the wavefront reconstructor for MCAO is decomposed into a few single-conjugate wavefront reconstructors for wavefront sensors, and the tomography problem for reconstructing atmosphere phase layers from phase output of these reconstructors. The tomography problem is solved using ART, a filtered backprojection method. We can generate MCAO reconstructors using this three-step approach for a variety of atmospheric models and asterisms containing both natural and laser guide stars. We have generated these reconstructors for apertures ranging in size from 5 to 25 meters and for turbulence models with Fried parameters ranging from about 5 to 50 centimeters.

**Minimum variance reconstructors.** Several candidate algorithms for MCAO/MOAO wavefront reconstruction have been developed that show $O(N^{3/2})$ performance, where $N =$ the number of AO degrees of freedom. An $O(N \log N)$ approach (based on Fourier analysis) also shows promise. Refinement of these techniques is still needed, but they are mature enough to implement in a prototype system simulation and laboratory experiments in the coming year.

**Optimal Wavefront Controllers.** The optimum Strehl controller for the case of Kolmogorov frozen flow has been derived and validated with simulations. The closed-loop optimum Strehl controller is quite different from the open-loop minimum variance wavefront estimator, since there is an interaction between measurement noise, the past history of measurements, and the wind speed. In Year 6 we will continue to investigate this method with regard to MCAO application and real-time implementation feasibility.

**Simulation tools:** Arroyo. We are developing a C++ class library called Arroyo to perform simulations of single and multi-conjugate adaptive optics systems. This library contains geometric and diffractive wavefront propagation through atmosphere turbulence layers and optical systems such as primary and secondary mirrors, wavefront sensors and deformable mirrors. The C++ 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, and with analytic approaches will help us make the transition from testing reconstructors in software to applying them to experimental data, e.g. from the Mt. Palomar’s Multiple Guide Star Unit (MGSU) and from the Laboratory for Adaptive Optics’ MCAO Testbed. The Arroyo simulation code had an initial release earlier this year, and a major release (V1.0) is scheduled for the end of the year. 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). The plan in Year 6 is to incorporate the fast tomography MCAO/MOAO algorithms which the CfAO has been developing. The CIBOLA covariance analysis code was developed for quick first-order PSF calculation and trade studies.

2.2.1.2.3 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. We will continue to pursue this relationship. In particular this coming year the Lockheed group is interested in modeling the deformable mirror actuator influence function, which is important to optimize for best fit in a Strehl-optimizing AO system.

Boston Micromachines Development of MEMS: During CfAO Years 4 and 5, LLNL was the lead institution in a DARPA project to develop MEMS deformable mirrors (DMs) for adaptive optics. Boston Micromachines presently markets a 1000 actuator device that is a direct result of this effort. Near term plans call for developing 64x64 (8,000 actuator) or larger devices. MEMS DMs are potentially useful as deformable mirrors in astronomical AO systems for extremely large telescopes if they can be made large enough and with high enough stroke.

Wavefront Sensor development: Caltech has partnered with Rockwell in the development of a high-speed low noise infrared wavefront sensor. Also, J. Nelson and J. Beletic are partnering with MIT Lincoln Laboratories in the development of a low-noise laser guide star specialized CCD.

This project has sponsored workshops on modeling and analysis, generally on a once a year 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.

2.2.1.2.4 Other Collaborations Outside CfAO

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. In CfAO Year 6, 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, as does the CfAO Associate Director for Theme 2.
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 the most 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 tests planned to take place using our laboratories.

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 early-on experience with the practical issues with such systems. The system at the Palomar Hale 5 meter telescope will have this year a multi-guidestar wavefront sensor unit which will provide on-the-sky tomography data sets for concept validation of tomographic wavefront sensing. Next year the University of Chicago’s laser guidestar will be added to the Palomar system.

As mentioned above, in January of 2004 we were co-organizers of a workshop at the Institute of Pure and Applied Mathematics at UCLA (see Figure 2.4).

![Figure 2.4. Web page from the IPAM workshop on “Estimation and Control Problems in Adaptive Optics” held in January 2004.](image)

**2.2.1.3 Future Plans for Year 6**

In Year 6 we plan to

1) Continue to develop theory and semi-analytic models in order to understand the wavefront reconstruction problems associated with multi-laser guide star, multi-conjugate correction for diffraction-limited imaging in the near-infrared on extremely large telescopes (ELTs).
2) Investigate phase reconstruction and control for ELTs, with emphasis on a Fourier domain approach that will yield accurate and computationally feasible algorithms. Analysis will focus on understanding the photometric and astrometric accuracy achievable, and on the robustness and predictability of behavior under changing seeing conditions.

3) Extend our statistically optimal wavefront controller results to the Fourier domain and to wind and boiling turbulence cases. These methods utilize a-priori statistical knowledge of Kolmogorov turbulence and the noisy wavefront measurements to determine a Kramer-Rao lower bound on wavefront error variance. The Fourier domain approach should allow, with some approximation loss, Kalman-filter predictive controller methods to become feasible for large systems with many deformable mirrors and many layers of turbulence. This work is being done in collaboration with Professor Donald Wiberg of the Electrical Engineering Department at UC Santa Cruz, and one of his graduate students.

4) Investigate hybrid Rayleigh/Sodium/natural guide star constellations for MCAO, and implement predictive filtering of natural guide star tip/tilt measurements to improve limiting magnitudes and sky coverage.

5) Investigate the use of adaptive secondary mirrors for “woofer-tweeter” wavefront control in MCAO and MOAO systems.

6) Evaluate the added value of uplink AO for the compensated projection of sodium laser guide stars.

7) Test the above system concepts in the laboratory.

8) Analyze and refine alternative AO system configurations and optical designs to sense the laser guide star light with a minimum of internal non-common-path aberrations.

9) Continuously develop of the Arroyo simulation code. Complete its implementation on a massively parallel supercomputer system. Use the code to validate analytic scaling law models and to compare with laboratory and observatory experiment results.

2.2.1.4 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 5 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, but of clear utility in Theme 2 as well).

2.2.1.4.1 Fiber laser for sodium-layer laser guide stars

In partnership with the European Southern Observatory, we continued to make progress on a new type of sum-frequency laser based on combining 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 generation crystal (SFG) as shown in Figure 2.5.
Our detailed study of the Nd³⁺ fiber laser system led us to a design space in which it is possible to achieve significant gain at in the 900 nm band while maintaining a controllable level of gain in the 1088 nm band. Optimization of the ratio of the fiber core and cladding areas permitted operation of the laser at room temperature by minimizing the gain at 1088 nm. We designed and procured our third iteration of the NDFA fiber in Year 5. The reduced core diameter (20 µm) of this fiber iteration allowed us to achieve 8 W of polarized light output from a two stage amplifier, with an M² of <1.18 (measurement limited). High beam quality is achieved by maintaining single-mode propagation in a multimode core. Higher order modes are eliminated by bending the fiber. A 6.5 cm bend radius was used to suppress the two higher order modes and to produce a single mode output in our latest fiber iteration. Spectra indicate that output at 1088 nm is down > 40 dB relative to 938 nm. The 1088 nm light can be completely suppressed by angle cleaving fiber ends and otherwise avoiding feedback to the amplifier. Addition of a second amplifier stage yielded 8 W output at 938 nm, with good polarization (100:1) using polarizers external to the cavity (Figure 2.6).

Figure 2.5  Schematic diagram of our fiber laser design.

Figure 2.6. Two stage 20 µm fiber amplifier produced 8 W output with good beam quality and polarization.
The primary issue for future scaling the 938 nm laser to higher output power is the onset of stimulated Brillouin scattering (SBS) in the fiber. SBS increases with fiber length, laser power, and inversely with core area. Our preliminary calculations indicate we should be able to achieve > 100 W output before hitting the SBS limit in the 938 nm fiber. In Year 5 we submitted a successful funding proposal to AURA to demonstrate CW power scaling of the 938 nm laser. These funds will allow us to procure a 150 W diode array for this purpose. In addition to assessing the scaling of the CW system to higher powers, we also modeled the expected output for a series of pulse formats. Based on these simulations, we submitted a successful proposal in response to an RFP under NSF’s Adaptive Optics Development Program. We proposed to develop a 10 W class pulsed fiber laser system with a pulse format that could be tracked through the sodium layer. This proposal is linked to a related AODP-funded project from J. Beletic and J. Nelson, who will develop a CCD that can track these pulses. The milestones for these AODP programs nicely complement our CfAO program. The first series of experiments will address the question of power scalability for pulsed systems.

Towards the end of January ‘04, the Toptica oscillator for the 938 nm laser died after 2.5 years of operation, and has been shipped back to Germany for repair (courtesy of ESO). However, we were left without any means of continuing our frequency conversion experiments. Because of the long repair time (due to import/export issues), we decided to develop an oscillator for use in the interim. This also provided us with important information on the tuning range of the NDFA, which will be used in finalizing our system design. We constructed a fiber oscillator using a 27-m piece of the double clad fiber and one 25 W diode pump laser. The oscillator produced ~ 800 mW at 938 nm, with spectral linewidth < 0.07 nm (measurement limited). The oscillator is tunable over 927-950 nm, as shown in Figure 2.7. It is actually desirable to operate the Nd:silica laser at longer wavelengths, as this allows the Er/Yb:laser to operate at shorter wavelength. The Er/Yb:laser has higher gain at shorter wavelengths, and is closer to the 1550 nm that is used in standard telecommunications products. The ability to use commercial off-the-shelf components for the Er/Yb:laser will reduce the overall cost of the system.

Figure 2.7  Newly designed oscillator is tunable over a range from 927-950 nm.
Another step towards an engineered system occurred when we visited the Nufern fiber facility. They can now provide an amplifier assembly which packages our specialty fiber in a small aluminum casing. The fiber inside is spooled at the requested bend radius. The casing comes with external quick connects that can be coupled to laser diodes for easy replacement and maintenance. In addition, we can now obtain fiber bundles that can be spliced to the fiber amplifier. These pigtails allow multiple inexpensive single stripe laser diodes to be coupled into the amplifier cladding, while the seed is coupled into the core via the center fiber in the pigtail. We purchased several of these connectors for testing. These commercial advances should provide a robust, fieldable laser system.

The final key technology is the use of periodically poled materials to generate visible wavelengths via sum–frequency generation. We selected PPLN, PPKTP and PPSLT to test. As our 938 nm laser was not initially available, we evaluated the reliability of these materials for frequency doubling 1064 nm light to 532 nm, which is more sensitive to optical damage than generation at 589 nm. PPLN was found to be unacceptable as a visible frequency converter, as this material suffers from photo-refractive damage at visible power levels as low as 100 mW. PPKTP can handle significantly more power at conversion efficiencies of up to 20% before the onset of significant degradation. The literature suggests that longer wavelengths of visible light have better reliability in PPKTP, so operating at 589 nm could improve the crystal reliability significantly. We developed a thermally induced spatial and temporal dephasing model of second harmonic generation to describe the conversion efficiency and its degradation of periodically-poled KTiOPO₄ (PPKTP) in a continuous-wave single-pass frequency conversion system. The model confirms our experimental finding that second harmonic power greater than 800 mW (15 kW/cm²) causes two-photon nonlinear absorption leading to time-dependent photochromic damage in PPKTP. This added absorption degrades the conversion efficiency from an initial value of 19% to an unrecoverable asymptotic value of ~ 8% in 2 hours at 145 kW/cm² of pump intensity. We will investigate this effect by comparing data from crystals of varying length. The model suggests that better materials, such as those being developed by Stanford University and PSI, Inc., could have significantly higher reliability and permit the creation of more efficient visible frequency conversion devices. Recent studies at Stanford University and elsewhere using second harmonic generation of 532 nm green radiation have shown that periodically-poled SLT (PPSLT) is basically free of PRD and GRIIRA and capable of long-term, high-power green light generation without degradation. They have demonstrated frequency conversion to 532 nm with 33% conversion efficiency, and have been operating at 5.5 W for over 1000 hours with no sign of degradation. We have established collaborations with researchers at Stanford University and at PSI to combine our test facilities for 589 nm generation with their crystal growth and poling capability.

2.2.1.4.2 Future plans for Year 6
We will complete our systems engineering design for a deployable CW laser system under our Cooperative Research and Development Agreement (CRADA) with Coherent Technologies Inc (CTI). We will refine our simulations to evaluate the ability of our design to operate in a pulsed format. This looks very promising, and an experimental demonstration of the limitations (SBS threshold in particular) is a milestone under the AODP program. Our full 5-10 W 589 nm laser system should become operational late in Year 5 or early in Year 6. We will characterize this system in Year 6.
We will down-select periodically poled vs bulk frequency mixing crystals. We have identified PPKTP as our baseline material at this time, but plan to test PPSLT as well. No damage was observed in PPKTP in 16% conversion efficiency tests at 532 nm over a 5 hour period. At current power levels, there has been no need for elliptical formatting. To date we have been limited by the YAG laser power available for testing the materials at 532 nm. With the availability of the 938 nm laser system, we decided to shift our emphasis to testing the materials for 589 nm generation directly. A go/no-go decision on the use of periodically poled materials will be made in conjunction with CTI by the middle of Year 6.

2.2.1.4.3 Industrial partnerships:
We developed a preliminary systems design and cost estimate for the CW fiber laser prototype. With this information in hand, we issued a Federal Business Opportunity Announcement to solicit an industrial partner to commercialize our technology. We finalized the selection, and are now in the process of writing a Cooperative Research and Development Agreement with Coherent Technologies Incorporated (CTI).

2.2.1.5 Completion of the Chicago Sum Frequency Laser and Implementation at the Palomar Laser Guide Star Test Bed
The Chicago Sum Frequency Laser (CSFL) consists of two pulsed, diode-pumped, modelocked 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 to zenith angle. Figure 2.8 shows a diagram of the laser.

![Figure 2.8 Schematic diagram of the Chicago sum-frequency laser](image)
The prototype laser achieved a power output of 3.5 watts in Jan 2004 and maintained a power level above 2.5 watts for 3 days continuous operation with minimal operator intervention and despite temperature fluctuations in the room of 20 degrees. The laser uses no active loops and is inherently stable due to a new cavity design.

In Year 5 a new gain module was engineered, with superior heat transfer characteristics and small area of 808 nm pump light concentration for the 1319 nm laser. This new gain module is optimally located where the theoretical beam matches the diode pump cross-section, with appropriate thermal lens compensation provided by a negative cylindrical lens in the cavity. There is a non-linear crystal in both source laser cavities to suppress relaxation oscillations, thus generating almost a rectangular laser pulse.

A new sum frequency converter was built with LBO crystals similar to those used in the AFRL Phillips Lab laser. We increased the 589 nm light output by measuring the source-laser beam diameters and matching them inside the Sum Frequency Generation (SFG) module using an appropriate telescopic lens combination. The new SFG module consists of three LBO crystals on a copper substrate with one lens and two spherical mirrors to focus the beam inside the three crystals. The temperature of the substrate is controlled by a thermo-electric cooler with a PID controller. The whole SFG module will be enclosed in an air-tight chamber and the pressure inside will be regulated to eliminate any phase mismatch between the beams due to dispersion. Figure 2.8 shows the high beam quality of the source lasers, and the single-pass generation of 589 nm light.

Figure 2.9. - Left panel: generation of 589 nm light with one crystal in a single pass.
Right panel: typical beam profile of our source lasers with $M^2 = 1.1$

We have shipped the laser to Palomar Observatory, where it will be installed in the Coudé room of the 200 inch telescope for use with the PALAO adaptive optics system. A photo of the laser while still in the lab at the University of Chicago is shown in Figure 2.10. We plan to propagate the laser along the Coudé axis of the 200-inch telescope, under separate funding. 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 speed) beam control system using motorized mirrors and quad-cells. The Palomar group is constructing an aircraft
detection safety system for the laser, as well as a laser launch telescope located behind the secondary mirror. The optical design of the laser launch telescope and the mechanical throw of the steering mirror facilitate pointing the laser beam anywhere inside a field of three arc min diameter.

2.2.1.6 Develop techniques for doing quantitative astronomy with laser guide stars

2.2.1.6.1 Point Spread Functions: Performance, Measurement, and Calibration

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 photometry and accurate positional information from adaptive optics images.

The 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.

A second important approach to understanding the PSF is the determination of the point-source response in real time, using the statistics of the atmosphere and data from the wavefront sensor to generate a PSF estimate for a long-exposure image. This PSF can then be used for image calibration, i.e. for photometric and positional measurements and for image deconvolution. Several groups within the CfAO are working on implementation of this type of real-time PSF estimation from Shack-Hartmann wavefront sensor data. Each group has developed a different approach to this difficult problem. To bring the groups together, the CfAO hosted a PSF reconstruction workshop in Victoria, BC in May 2004 to share current progress, to identify what degree of PSF knowledge is required for different scientific goals, and to identify future directions for research (e.g. the application
to MCAO). The two-day workshop had a much higher attendance than we had originally anticipated, including groups from Europe and Canada as well as the US. It was a resounding success.

We have applied deconvolution techniques to several typical astronomical imaging problems. These include images of a Galactic Center star cluster, of the sodium laser guide star spot at the Starfire Optical Range, of nearby active galactic nuclei, and of planetary bodies such as moons of the giant planets and asteroids. Figure 2.11 shows images of the asteroid 121 Hermione, taken by F. Marchis with the Keck Telescope AO system. It is clear from the raw image, but clearer still in the deconvolved image, that this asteroid has a double-lobed “peanut” shape.

We have written a new deconvolution code called AIDA - the CfAO/UCSF deconvolution process (Franck Marchis and Erik Hom). We rewrote, optimized, and increased the computational speed of MISTRAL, and demonstrated a factor of 10-50 gain in processing speed. We also coded a MISDAC (MISTRAL + IDAC) deconvolution method for low signal-to-noise data, and are testing it now on planetary science images (real and simulated) as well as on biological images from fluorescence microscopy for J. Sedat's laboratory at UCSF. When testing is complete, this code will be made publicly available

2.2.1.6.2 Advances for the Sodium-Layer Laser Guide Star AO System at Lick Observatory
At present the sodium-layer laser guide star at Lick Observatory is the only such system available for astronomical science on a regular basis. Hence it is important to use this system as a test-bed for astronomical science using laser guide stars.

In order to improve the on-sky efficiency of astronomical observations done with laser guide star AO at Lick, in Year 6 we will undertake 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 should significantly improve 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.

2.2.1.6.3 Design Study for a Next-Generation Laser Guide Star AO System at the Keck Observatory
In the coming year we are also undertaking a project to develop a feasible point design for the next-generation laser guide star AO system at the Keck Observatory. The goals for this system include extremely high near infrared Strehl ratios, high Strehl stability, near-complete sky coverage and a good knowledge of the delivered point spread function
across the field of view. The concept has been dubbed KPAO, for Keck Precision Adaptive Optics.

The top-level KPAO requirements are very demanding and are in many ways similar to those for future 30-m AO systems. For example we will be pursuing a total rms wavefront error budget of 120 nm, and we will be using multiple laser guide stars for tomographic wavefront reconstruction. There is therefore very strong overlap with ELT AO design efforts, and with CfAO’s Theme 2. This project will stimulate community collaboration on the KPAO design effort through funding of a postdoctoral researcher. The Keck AO team has participated in two similar CfAO funded proposals (postdocs: Marcos van Dam and Antonin Bouchez), both of which have proven to be very successful and productive collaborations with the CfAO. Keck Observatory has committed FY05 and 06 resources to support the development of a conceptual level design for KPAO. The PI of this project, Chris Neyman, was recently appointed to provide full-time leadership for the KPAO design and analysis efforts. He will be supported by the Keck Observatory’s AO team.

We will focus our KPAO modeling, design and experimental efforts in these specific areas: 1) Evaluation of the difference between full tomographic reconstruction and cone-effect only correction. 2) Wavefront sensor calibration to the 20 nm level. 3) Conceptual design for an AO system to correct upward traveling laser guide star light.

Some of the concepts developed will be tested in the Laboratory for Adaptive Optics at UCSC.

2.2.1.7 Astronomical Science Related to AO on 30-m Telescopes

2.2.1.7.1 CATS: The CfAO Treasury Survey
In Year 5 we continued work on an important scientific legacy project from CfAO: the CfAO Treasury Survey (CATS). We are using adaptive optics to observe a large, deep sample of galaxies in the early Universe with the ultimate goals of 1) observing the assembly of galaxies from smaller subunits to larger ones like our own Milky Way, 2) measuring the rates of star formation and the evolution in stellar populations, 3) discovering the highest redshift supernovae, and 4) identifying central active galactic nuclei (AGN) 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 to explore some of the grandest and most profound problems in cosmology.

CATS is planned to continue through all of the 2nd 5 years of CfAO, and will focus on the largest Hubble Space Telescope fields designed for faint galaxy surveys. These presently include two GOODS (Great Observatories Origins Deep Survey) fields (north and south), the GEMS field (extension of GOODS-S), COSMOS (an equatorial field), and (added this year) one of the four DEEP fields known as the Extended Groth (a northern field). These regions of the sky are being intensively studied by a suite of the world's largest and most powerful ground and space telescopes that span a full range of energies from the radio to X-rays. The non-X-ray space telescopes will achieve close to diffraction limited performance and 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 the Hubble Space Telescope. The near-IR wavelength range 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, thus allowing direct comparisons to extensive optical studies of local galaxies. The CATS observing program is envisioned to take many dozens of Keck, Gemini, and Subaru nights, with significant repeat observations to reach fainter limits, gain larger fields of view, and detect variable active galactic nuclei and supernovae.

A pilot study from Year 4 successfully launched this project. CATS expanded its membership in Year 5 to include more junior members, and participants with access to the Gemini, Subaru, and CFHT telescopes (all with AO systems). The Space Telescope Science Institute was contacted and has agreed to collaborate in the development of a community-friendly CATS archive and database.

Besides providing a major legacy science program for CfAO, CATS is also a superb “Center mode” activity - by unifying previously separate and fragmented Center science programs; by providing an excellent technology platform for pushing and demonstrating the power of AO; by disseminating forefront AO data and associated reduction and analysis tools; and by focusing on the most intensely studied fields in the sky, a vehicle for gaining much wider community interest and expertise in AO. Although we began this project using natural guide star AO, laser guide star systems will be crucial for the CATS project to achieve high sky coverage of the deep fields it is observing.

In Year 5 we obtained the first Keck natural guide star AO observations of the COSMOS field, and obtained Lick laser guide star observations of the GOODS-North field. We have assembled a set of web pages that organize our galaxy catalogues and observations (http://www.ucolick.org/~jmel/cats.html). We found that our data from the Lick laser guide star system (see Figure 2.12) are of good enough quality to be included along with Keck, Subaru, and Gemini data in our database, despite the fact that the Shane telescope at Lick is only 3 meters in diameter.

![Figure 2.12](http://www.ucolick.org/~jmel/lasers.html) 

Figure 2.12. A portion of the CATS web pages, showing laser guide star data from Lick Observatory (H band, infrared) and visible-light data from the Hubble Space Telescope.
The CATS team is currently working on several papers with the Lick and Keck data from the 2003-2004 observing season. Topics include 1) extremely red galaxies (EROs) which are galaxies that are basically undetected in the HST images, 2) compact galaxies that appear very blue in the HST images but may have older (redder) underlying stellar components, 3) disk and bulge evolution with redshift, and 4) a very exciting discovery, galaxies undergoing merging events. As is shown in Figure 2.13, we have detected a group of objects with separations from bright galaxies between 0.5 and 1 arc sec. These objects, probably similar to our own Magellanic Clouds, are likely to merge with the host galaxy within a billion years (unlike the Magellanic Clouds). By doing so they could help explain both the kinematically distinct populations of stars seen in local galaxy disks and the presence of stars in a thicker disk component. More surprisingly, we don’t see counterparts of these companions at larger angular separations. Our hypothesis is that these companions are quiescent until they reach 10-20 kpc separations, and then they are stimulated to form stars at a rapid rate. With our new data within the GEMS field, we are finding support for this hypothesis. Both of the infrared close companions seen within our AO images of GEMS are much bluer than their host galaxies. Figure 2.13 shows how they could easily be confused as a major merger if only the optical images from HST were available. Only with the infrared images can we see that the redder “host” is an order of magnitude more massive than its companion.

![Figure 2.13](image)

**Figure 2.13** The histogram of the number of galaxies with a nearest neighbor at a given separation (in arc seconds). The red curve is the expected distribution (dashed lines are 1 sigma) and the black lines are the observed distribution. On the right, the panel shows an infrared image and an HST image of one of these close companions. The much brighter appearance of the companion in the optical image shows that its star formation rate is comparable to the host, while its mass is much lower.

We began a sub-project of CATS, focusing on compact galaxies seen in the CATS fields and comparing them with nearby compact galaxies. The CATS team has been holding
regular video conferences, which are working meetings involving CfAO members as well as our collaborators from other institutions.

**2.2.1.7.1.1 Future Plans and Year 6 Activities:**
Year 6 of the Center will see several firsts for the CATS program. It is expected that both the laser guide star system and the new OSIRIS imaging spectrograph will be fully commissioned on the Keck 2 Telescope. We aim to complete about 5 nights on the Keck Telescope observing both natural and laser guide star targets in the GEMS, COSMOS, and EGS fields. We will continue the use of the laser guide star AO system at Lick Observatory to study the brighter galaxies in the CATS fields, to study nearby compact galaxies, and to gain experience and understanding of the characteristics of laser guide star versus natural guide star AO images of objects at high redshift. Using the Lick laser guide star AO system will continue to be important even when the Keck laser is fully available later this year, since the Lick laser guide is a mature system while Keck system may experience “birthing pains” during Year 6.

OSIRIS, a soon-to-be commissioned infrared spectrograph for Keck, will be key to our observations in Year 6 and beyond. Due to its extremely low backgrounds between night sky lines and at adaptive optics spatial samplings, the OSIRIS instrument will reach point source sensitivities more than 2.5 times fainter than any previous infrared spectrograph. The integral field capability will also greatly increase the efficiency in studying crowded fields like the bulges of nearby galaxies and complex morphological structures such as high redshift galaxies.

Spatially resolved spectra from OSIRIS will be used to search for central black hole activity, and to measure the star formation rate and stellar ages in the disk and bulge. In cases where multiple lines are detected we can also determine the dust content of the galaxy. OSIRIS spectra can also be used to measure the rotation rates within the galaxies and from this determine the mass distribution. Recent tidal interactions and mergers will also leave a spectral signature both in the emission line ratios and kinematics. Bright HII regions in high redshift galaxies are also ideal unresolved targets for the OSIRIS instrument. Without integral field capabilities, a slit-based spectrograph would be unable to locate such regions in reasonable amounts of observing time. Figure 2.14 shows a full simulation of a high redshift galaxy with a "faint" Hα emission line. It is equivalent to what would be expected from a total star formation rate of 10 M☉/year at a redshift of one. The emission line is not only easily detectable, but clearly shows a 200 km/sec rotation rate on a scale length of 5 kpc. A slit placed randomly on the galaxy could easily miss the rotation curve, or measure it along the wrong axis. This simulation has been done with a complete modeling of the instrument and atmosphere, and then was passed through our early version of the data reduction pipeline.

Figure 2.14. Complete simulation of rotation curve of a high redshift galaxy with a faint Hα emission line.
Using the optical, x-ray and mid-IR data that will be publicly available, along with AO imaging data and OSIRIS spectra such as that shown in Figure 2.14, we will begin characterizing the galaxies in the CATS fields. We will test point spread function characterization schemes both for the natural and laser guide star targets. This is a crucial step before releasing data to the community at large. We will begin work on the CATS archive in conjunction with STScI and the other GOODS teams.

2.2.1.8 Partnerships with Industry

We partnered with several industrial partners for the construction of the OSIRIS instrument which will play a crucial role in the remainder of Year 6 and which was supported in its early design phase by CfAO. Our primary industrial partners were SSG Inc. who manufactured a very complex set of metal mirrors (six off-axis conic sections arranged in two three mirror anastigmats), MEMs Optical who created a custom lenslet array for the focal plane, and Diffraction Products who created a large custom grating with very low groove density and high throughput.

2.2.1.9 Adaptive Optics Imaging of Solar System Bodies

_Uranus and its Rings:_ Marcos van Dam, a CfAO postdoc, successfully optimized the Keck AO system so that it could use extended objects such as Uranus as wavefront reference sources. Our October 2003 images of Uranus resolved the faint rings (Figure 2.15). We derived highly accurate ring particle albedos for each ring and for all the inner satellites of Uranus.

![Figure 2.15. - Uranus and its rings in H band, from October 2003. This image is a 5 minute integration, to emphasize the rings. Since Uranus itself is so much brighter than its rings, the central image of Uranus uses a highly attenuated color map.](image)

_Neptune’s Rings._ Neptune’s ring system is much more tenuous than that of Uranus, with two major rings (the Adams ring and the le Verrier ring), a few even fainter rings, and prominent ring arcs embedded in the Adams ring. These arcs were first imaged by Voyager in 1989, and subsequently\(^4\) with the NICMOS infrared camera on the Hubble Space Telescope in 1998. Figure 2.16a shows the ring arcs as imaged with Keck adaptive optics in October ’03. The inset shows an individual 1-minute exposure of Neptune itself. In order to enhance the contrast in the rings, we combined 36 1-minute exposures and


median-filtered them. Figure 2.16b shows the main rings after deprojection and shifting in longitude to correct for Keplerian motion. Since 1989 when Voyager flew by Neptune, the rings have evolved. Most dramatic are the changes in the two leading arcs: Liberté is on the verge of disappearing completely and Courage jumped a full 8 deg ahead in its orbit. Thus our observations reveal a ring arc system that is surprisingly dynamic\(^5\) (de Pater et al 2004b).

Other observations: Neptune wind patterns and cloud-top altitudes, new positions for inner Neptune moons, Io volcanoes in K', L', and Ms bands and thermal budget of Io, Titan 3D image cubes to derive surface albedo, tropopause cirrus opacity, stratospheric hazes; search for binary main-belt asteroids and Trojans; discovery that 121 Hermione is peanut-shaped.

2.2.1.9.1 Future Plans for Year 6

Future Plans for Year 6

We will continue our observations and interpretation using adaptive optics for planetary science. We plan to do laser guide star observations from both the Lick and Keck observatories, targeting asteroids, transneptunian objects, and the Jovian ring system. We plan natural guide star observations of the Neptunian system (rings, satellites, atmosphere), Io, and Titan.

2.2.1.10 Adaptive Optics Studies of the Galactic Center

The center of our Milky Way Galaxy is now known to contain a black hole with more than three million solar masses, 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. We therefore are studying Adaptive Optics performance on this field with a variety of different systems (Keck vs. Gemini; NGS vs. LGS) from the point of view of point spread function quality, overall Strehl, stability, and anisoplanatism. In addition we are investigating the astrometric and spectroscopic accuracies that can be achieved in such a crowded stellar field. These results will be applicable to a number of different applications and are of large interest to the general CfAO community.

Astronomically, we 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 allowed us 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 Year 5 we 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 mas (1 σ) of the Galaxy's central supermassive black hole and the unique radio source Sgr A*. See Figure 2.17. While in 2002 this source (SgrA*-IR) was confused with the stellar source S0-2, the two sources were shown to be separated by 87 mas in 2003. This enabled the new source's properties to be determined directly. On four separate nights, its observed L' magnitude ranged from 12.2 to 13.8, which corresponds to a dereddened flux density 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 at L' 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, we concluded that it is associated with the central supermassive black hole. The short timescale for the 3.8 μm flux density variations implies that the emission arises quite close to the black hole, within 5 AU, or 80 Schwarzschild radii. We suggest that both 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 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.

Photometry of all the sources detected at L' in maps obtained at Keck during four separate observing runs 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.
We have gone back to older AO images and carried out a complete re-analysis of all our existing data (improved frame selection, improved imaging weighting, and improved resampling). 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 arcsec of the Galaxy’s central dark mass, we identified 22 proper motion stars, 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 reveal orbital solutions around the black hole. A simultaneous orbital solution pinpoints the Galaxy's central compact dark mass to within ±1 milli-arcsec and, for the first time from orbital dynamics, limits its proper motion to 0.8 ± 0.7 mas/year. The estimated central dark mass from orbital motions is $(4.0^{+0.3}_{-0.3}) \times 10^6 (R_0/8kpc)^3 \, M$. 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 to 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.

2.2.1.10.1 Planned Future Work in Year 6

The Galactic Center is a difficult AO target: it is at high airmass as seen from the telescopes in Hawaii, and has no bright star nearby to use as a wavefront reference. We plan 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. We 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 final images, but are obtained much less efficiently, in terms of telescope time, than longer exposures. 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. Likewise, lower Strehl images are not as sensitive to extended structures. We have begun this type work by comparing the Keck and Gemini AO images which have very different exposure times and Strehls.

A related and important component of our 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 we are limited by our PSF reconstruction, and the collaborative work this past year has dramatically increased our sensitivity to faint sources in the crowded central region and improved the astrometric precision on known sources.

While the above work focuses on imaging, AO now allows us to obtain spectra as well. We therefore plan to study the above trade-offs for spectroscopy with the additional parameter of spectral resolution to consider.
2.2.1.11 Galaxy Activity and Evolution via Laser Guide Star AO

We are studying nuclear regions of nearby active galaxies, and comparing them with the cores of "normal" galaxies in which there is no evident black hole activity. There is good evidence that there are black holes at the centers of most galaxies. However, in only a subset of these galaxies is the central black hole actively being fueled by accretion of matter from regions at larger radii. For nearby active galaxies, our goal is to investigate the morphology and kinematic structure within the inner kiloparsec of the central black hole. It has been suggested that infall to the central black hole may be mediated by inner spirals, inner bars, shocks, or some other mechanism that allows matter to lose angular momentum and be captured by the gravitational potential of the central black hole. We are using laser guide star adaptive optics at Lick Observatory and data from the Hubble Space Telescope Archive to compare the nuclei of active galaxies with those of their quiescent counterparts, to address whether we can observe systematic differences between them, both in kinematics and in morphological features such as bulge profiles and sizes, inner spiral structure, and inner bars.

To date we know of only four scientific papers (on any topic in astrophysics) that have been published using laser guide star adaptive optics. Our project is a proving ground for obtaining extragalactic scientific data from laser guide star AO and will produce data analysis methods of general use for other laser guide star observers. Further, our work is providing cross-checks among data from the Lick and Keck laser guide stars and data from HST, to develop and test appropriate data analysis methods. This type of quantitative work is badly needed in order to establish the credibility of laser guide star adaptive optics for 30-m telescopes of the future.

In Year 5 we completed the data reduction and analysis for images of all our Lick AO targets. Additionally, we have compiled a large set of HST archival images and spectra. Here we will illustrate how these datasets complement each other by focusing on the galaxy IC 342. This galaxy is a very nearby (~3 Mpc) SAB(rs)cd galaxy. Figure 2.18 shows the Digital Sky Survey image of this galaxy. The green bar represents one arc minute. Though IC 342 does not possess an AGN, it does have a significant amount of nuclear star formation and thus HII emission.

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We obtained broad and narrowband images of IC 342 from the Lick laser guide star AO system, as well as broad and narrowband HST images and HST spectra. In Figure 2.19 we show the HST F555W image and in Figure 2.20 our Lick Ks image. The bar on each represents one arc second. It is clear that the Ks image has a much smoother light distribution and thus is better suited than the F555W image for creating a surface brightness profile. Figure 2.21 shows a (V-Ks) color map for this galaxy using the HST F555W image and our Lick LGS Ks image. This color map highlights the regions of heavy dust obscuration: redder regions are areas more strongly obscured by dust, while bluer regions are less obscured.

Figure 2.18 The nearby galaxy IC 342, a nearly face-on spiral galaxy. This image shows the entire galaxy, and is from the Digital Sky Survey. The green line indicates one minute of arc.

Figure 2.19 HST F555W (visible-light) image of the nucleus of IC 342. Green bar indicates one arc second. Note the patchy dark lanes of dust across the center of the image.

Figure 2.20 Lick laser guide star AO Ks image of the nucleus of IC 342. The black bar indicates one arc second. Note how much smoother the light distribution is in the Ks image, compared to F555W. This is due to the fact that the near-IR light probes through the dust; we are seeing the background distribution of stars in the galaxy core. The smooth Ks image is well suited for making surface brightness profiles.

Figure 2.21 V-Ks color map of IC 342, from data in Figures 19 and 20. The bar indicates one arc second. Redder regions are areas of increased dust obscuration while bluer regions indicate less obscuration. Color maps such as this one highlight the dust in the galaxy.

Figure 2.22: Lick laser guide star AO Br-γ image of IC 342 (continuum-subtracted). Bar indicates one arc second. Images such as this are useful for choosing Lick LGS AO spectroscopic targets and for interpreting emission line spectra, since they provide a 2-dimensional map of the emission line gas.
Figure 2.22 shows one of our narrowband laser guide star images from Lick. This is a continuum-subtracted Br-γ image highlighting the distribution of ionized gas around the nucleus. Narrowband images such as this help us determine which objects have strong emission lines and will make good Lick LGS spectroscopic targets, and they tell us where we should position the slit for such observations. IC 342 is an ideal candidate for Lick LGS spectroscopy and will be one of our high priority spectroscopic targets during Year 6.

2.2.1.11.1 Future Plans for Year 6
Spectroscopy of nearby galaxy centers will be a major focus in Year 6. We will obtain and analyze Lick laser guide star AO near-IR spectra of a selected subset from our galaxy sample. We will complete the data reduction, analysis, and interpretation of HST STIS spectra in our galaxy sample. In the area of AO imaging, we will complete reduction and interpretation of our archival HST imaging data, as well as any new Lick imaging data that we obtain. Using the HST data, we will create unsharp-masked images (dust maps) for the 10 galaxies for which we have not yet done this. We will compute surface brightness profiles for those galaxies having only HST images. (We will have completed surface brightness profiles for Lick AO galaxies in Year 5.) We will complete a well-defined Keck AO study of a subset of our galaxy target sample (a few of the most interesting objects). This may include some laser guide star targets if the laser is available to us.
2.2.2. Theme 3: Extreme Adaptive Optics (ExAO): Enabling Ultra-High Contrast Astronomical Observations

2.2.2.1 Introduction
Extreme Adaptive Optics (ExAO) focuses on the development and utilization of AO systems and instrumentation to enable revolutionary ultra-high-contrast astronomical observations, with the primary goal of the discovery and characterization of extrasolar planets through direct imaging, thereby providing new insights into planet properties and formation. In order to accomplish this goal, in Year 4 a collaboration of all members of the ExAO theme proposed an ambitious, highly collaborative, multi-institutional, long-term project, including both scientific and technological components. The main objective of this project is the deployment of a dedicated ultra-high-contrast system for an 8-10 meter telescope to image self-luminous extrasolar planets at contrast levels $> 10^7$.

Since it was recognized that the CfAO lacked sufficient resources to fund the entire development of such a system, the project was arranged so that the CfAO (and the Moore Foundation Laboratory for Adaptive Optics – the LAO) would fund preliminary investigations on the basic feasibility of ExAO, to lead into a conceptual design study. The goal of this process was to produce a detailed vision of a feasible ExAO system, with detailed performance predictions, costing, and a science case, that could be used to persuade external agencies to fund the development of such a system. The success of this strategy can be seen in the decision of the Gemini Observatory to select ExAO as one of its next-generation instruments.

During Year 5, we will complete a design study for such an instrument appropriate for the Keck Telescope, the eXtreme AO Planet Imager or XAOPI. We also began a detailed conceptual design for a similar instrument for the Gemini telescope, the Extreme AO Coronagraph (ExAOC), after having competed for and been awarded a contract from Gemini in support of this design study. For the Gemini ExAOC design study, we have significantly expanded our existing CfAO partnership to include several new institutions in the U.S. and Canada with additional expertise and experience in deploying adaptive optics systems on Gemini, and in building coronagraphic and multi-wavelength, high-contrast imaging systems.

The ExAO theme takes explicit advantage of the “Center mode of operation,” since this project is significantly larger in scope and duration than a typical NSF single PI project, and can be accomplished only by coordinating and combining the efforts of numerous researchers at multiple institutions. Developing key enabling technologies for an ExAO system emphasizes multi-disciplinary collaborations, including links to engineering researchers and industrial partnerships. Development of these key enabling technologies also strengthens links between astronomy and vision science. MEMS deformable mirrors are being developed for both applications, and current AO system performance characterization activities address both astronomical and vision science systems. In addition, the design and implementation of an ExAO system with $10^3$-$10^5$ degrees of freedom on the current generation of large telescopes is an important step towards AO for extremely large telescopes, which require a similar number of control points.
2.2.2.2 ExAO Theme Accomplishments

2.2.2.2.1 High-contrast science with current AO systems

The team led by Andrea Ghez at UCLA continued the program of imaging protoplanetary disks in scattered light in the thermal infrared where the quality of the correction provided by the Keck AO system is excellent (Strehl ratio of 60% and more). Following analysis of the dust grain population in the dusty ring surrounding the young binary system GG Tau\(^{11}\), they obtained new 3.8 and 4.7 micron deep images of the HV Tau young multiple system. The third stellar component of the system has been found to be hosting a small, 50 AU-radius, circumstellar disk viewed in an edge-on configuration so that the view to the central star is totally blocked, and only starlight that has scattered off the upper layers of the disk is received. The Keck AO system provides 3.7 and 4.8 micron images of very similar spatial resolution to previous 0.6 and 0.8 micron HST/WFPC2 images of the system\(^{12}\). The longer wavelength Keck observations permit probing of the dust grains located deeper into the disk because of the smaller dust opacity at longer wavelength, and enable more sensitivity to the presence of grains larger than those found in the interstellar medium. Combining these two aspects, one can study the possibility of dust settling toward the disk midplane and/or grain growth through coagulation of small particles. Both phenomena are anticipated to take place during the process of planet formation.

This study perfectly illustrates the potential of future ExAO systems for the study of protoplanetary disks as they will permit similar studies at shorter wavelengths at which the thermal background is much reduced and, consequently, where many more disks can be imaged and analyzed.

The team led by James Graham at UC Berkeley completed commissioning of the IRCAL AO polarimetry mode at Lick and has begun a major campaign to observe Herbig Ae/Be stars. Observations in Year 5 were very productive, returning high-quality images of

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circumstellar dust around several young stars in both natural and Laser Guide Star mode. The observations show that circumstellar structures around Herbig Ae stars are morphologically similar to those around the lower-mass T Tauri stars, supporting the conclusion that these two classes of objects form in similar manners.

Laser guide star (LGS) observations of the stars LkHa 198 and LkHa 233 were published in the February 27 issue of Science\(^\text{10}\). A second paper is in preparation on LGS observations of the intriguing object LkH\(\alpha\) 225, a binary star whose members are apparently linked by a filament of dust, possibly a tidal streamer torn from circumstellar disks in a close encounter.

**2.2.2.3 eXtreme AO Planetary Imager (XAOPI)**

In Year 5, our primary goals for the XAOPI project were:

1. Studies of the key technical uncertainties for an ExAO system, including wavefront sensing, calibration, and coronagraph properties
2. Completion of a conceptual design document – the XAOPI “Red Book” – primarily oriented towards a Keck-based system
3. Vigorous pursuit of the opportunity to build a Gemini ExAO system.

During Year 5, we carried out and published detailed simulations of XAOPI’s innovative spatially-filtered wavefront sensor\(^\text{13}\) (SFWFS). These simulations show that in addition to improving mid-frequency residual atmospheric errors by 1-2 orders of magnitude, the SFWFS also reduces the sensitivity of the system to residual static errors such as Keck segment phasing errors, and also reduces the sensitivity of a Shack-Hartmann system to changes in spot size, a crucial issue given the extremely challenging static error requirements for ExAO.

We published papers on the structure of the ExAO PSF\textsuperscript{14} allowing separation of diffraction and phase errors and hence prediction of the PSF from the power spectrum of the residual wavefront. We also used end-to-end wave-optics simulations and faster but less accurate stochastic Fourier simulations to develop simulated long-exposure PSF models. Our coronagraph group simulated coronagraphs for the segmented Keck telescope and developed an analytic framework for understanding Lyot coronagraphy on massively segmented telescopes\textsuperscript{15}. Calibration of non-common-path errors is a key issue for ExAO. The calibration team led by Kent Wallace (JPL) and James Lloyd (Caltech, now Cornell) developed a novel strategy using pupil-plane imaging at the science wavelength in the science camera\textsuperscript{16}.

With CfAO funding at LLNL and LAO funding at UCSC we have developed an ExAO test bed, combining metrology provided by the LLNL phase-shifting diffraction interferometer (PSDI) and extremely high-quality optical components\textsuperscript{17}. The test bed shows an end-to-end wavefront error of <1.5 nm RMS over a 10 mm pupil with a superpolished flat mirror. Using shaped pupils to control diffraction, we have demonstrated imaging contrast >10\textsuperscript{7}. In June 2004 we installed a 1024-actuator Boston Micromachines MEMS deformable mirror and successfully flattened it to <1.8 nm rms wavefront error over the controllable range of spatial frequencies, 4-16 cycles/pupil\textsuperscript{18}.

Figure 2.26: Slice through the PSF produced with a prolate spheroid pupil from Princeton University. Three data sets are included in this graph. The solid line is the saturated image. The vertical dotted line represents the edge of the mirrored focal plane block. To the right of the block the saturated image is affected by bleeding from nearby pixels. Contrast below $10^{-7}$ is achieved on the right side of the graph. To the left of the block, the noise floor of the system at $10^{-8}$ can be seen. The two dotted lines at upper left trace out the core of the image.

Figure 2.27: Block diagram of XAOPI ExAO system
The most significant development in the quest for ExAO system funding has been the selection of an extreme AO coronagraphic imager/spectrometer (ExAOC) system as one of the four next-generation Gemini instruments. The CfAO put together a multinational partnership, with additional collaborators (HIA, University of Montreal, and the American Museum of Natural History), and submitted a successful proposal for the ExAOC study. Our strategy has been to use the limited Gemini funding for this design study to cover areas not included in our CfAO work, such as an integral field unit and Gemini-related systems engineering; CfAO and Moore Laboratory for Adaptive Optics funding is supporting the participation of CfAO groups in this study.

2.2.3.1 Status of Year 5 Milestones:

Publish results of models of behavior of continuous and segmented MEMS and conventional DMs in high-contrast imaging

*Status*: Published by Poyneer et al. 19 2003.

Publish papers describing XAOPI concept, performance, and science reach


End-to-end simulation predicting ExAO sensitivity including telescope and MEMS properties.

*Status*: Simulations in progress (as of July 2004).

Operational monochromatic ExAO testbed in Laboratory for Adaptive Optics with 1000-actuator MEMS and <5 nm RMS WF error in controlled frequency range

*Status*: MEMS now installed in ExAO testbed and first closed-loop results show <2 nm RMS WF error.

Publish paper on Keck L’ imaging of circumstellar dust

*Status*: Published (Duchene et al. 11 2004).

Design (and publish) preliminary optical design for XAOPI including basic coronagraph. Status: Preliminary optical design complete and papers presented at 2004 SPIE conference.

Preliminary Design Review for XAOPI (Contingent on XAOPI external funding) Status: XAOPI design schedule has been adjusted to accommodate Gemini schedule – conceptual design review will take place in about February 2005.

In addition, two Year 6 milestones have already been met:

Publish paper on Lick polarimetry results Status: Published in “Science” (Perrin et al.).

Demonstrate equivalent contrast $>10^7$ using ExAO test bed and Lyot coronagraph. Status: By using a shaped-pupil coronagraph we have demonstrated contrast $>10^7$ in our ExAO test bed, even without a Lyot stop or deformable mirror. These results are being submitted for publication.

We also continued our collaboration with Boston Micromachines on MEMs technology development, funded by the LAO. We have a contract for delivery of a series of 1024-actuator continuous-facesheet MEMS devices, leading towards a goal of zero bad pixels over the illuminated area of the mirror. Detailed characterization of the stability and controllability of these mirrors will be carried out in the LAO. We have also commissioned the conceptual design of a 4096-actuator DM.

2.3 Future Plans

The plans for the ExAO effort have adapted significantly to changing external conditions – most notably the opportunity to build a Gemini instrument, which (for the construction phase) would be almost fully funded by Gemini itself. Our plans for Year 6 and especially Years 7-10 are necessarily contingent on the results of the design study and of Gemini funding decisions.

The Gemini ExAOC design study runs from ~June 2004 to ~February 2005. Gemini funding for this study is ~$200K, which is inadequate for a detailed conceptual design for a $10M+ instrument well beyond the current state of the art. Therefore, we opted to use Moore LAO funding to co-fund the Gemini effort, and CfAO funding to support distinct but complementary goals. Consequently, the first part of each ExAO subproject in Year 6 is focused towards those activities necessary for enabling completion of the Gemini design study. The bulk of the direct Gemini funding will be used by the Canadian institutions not already part of our CfAO ExAO efforts – HIA and University of Montreal.

Gemini is funding two conceptual design studies. At the conclusion of these studies, one group could be selected to build a complete instrument. However, Gemini has not yet secured funding for its ambitious instrument construction program. Consequently, we believe it likely there will be a delay between completion of the conceptual design study and the beginning of the construction phase – most likely, the full Gemini ExAO contract would not begin until FY06. During the intervening period – February 2005 through late 2005 – CfAO efforts will be focused on three primary goals:

1) **Risk reduction**: Continued research in areas identified during the conceptual design phase as high-risk. We expect these areas to include precision calibration (JPL/LAO), and
demonstration of high-contrast imaging with aberrations corrected by MEMS mirrors (LLNL/LAO).

2) **Keck (and TMT) ExAO development:** Once the Gemini study is completed, we will return to the question of ExAO on a segmented telescope, both for Keck and to understand the fundamental limits to ExAO on TMT. This will include work on coronagraph designs for segmented telescopes (STScI), as well as wavefront control of phase discontinuities (LLNL). There will be an increasing emphasis on hardware testing at the ExAO testbed at UCSC’s LAO and at the JPL High-Contrast-Imaging-Testbed.

3) **Ongoing science with current AO systems:** As in past years, a vigorous program in ExAO science with existing AO systems is an important component of our research, allowing us to understand the science drivers for future ExAO and the properties of current technology such as telescopes, AO systems, etc.

Below we summarize future activities at each institution:

**LLNL (CfAO and LAO funding):** Complete development of AO control algorithms and realtime software architecture. Project management and leadership. Demonstration of high-contrast imaging goals using MEMS mirrors and realistic aberrations on LAO testbed.

**UC Berkeley (CfAO funding):** Complete development of a quantitative ExAO science case. Science with Lick and Keck AO systems.

**STScI (CfAO funding):** Complete 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):** Design an ExAO calibration architecture and verify its performance in simulation. Preliminary testing of calibration architecture at JPL, Palomar, or LAO.

**UCSC (LAO funding):** Complete a Gemini ExAO optomechanical design and software architecture. Carry out high-contrast experiments on the LAO ExAO testbed.

**UCLA:** High-contrast science with Keck AO including Keck laser guide star.

**Cornell:** James Lloyd is beginning a tenure-track faculty position at Cornell. Modest continued CfAO funding will allow him to participate in the ExAO design as a crucial connection between the calibration and coronagraph groups.

We will also explore partnerships with CCD/camera vendors to meet the demanding sensor requirements of ExAO, and we will explore collaborations with optics firms in the US and Canada on subsystems of the Gemini ExAOC instrument.

Plans for Year 7 and beyond are contingent on Gemini’s awarding of the construction contract. Selection and full funding by Gemini will be the most desirable outcome for the CfAO ExAO effort. It will allow us to carry ExAO forward to its ultimate conclusion, and free up funding for new ExAO areas such as AO for ELTs, innovative wavefront sensing concepts, etc. If we are not selected, ExAO efforts directed towards the ExAO system may begin to ramp down (except as necessary to pursue funding for Keck ExAO); a determination on this will be made during the proposal cycle next year.
2.2.3 Theme 4: Vision Science

2.2.3.1 Introduction
Scientists and engineers participating in the Vision Science Theme have agreed to focus on the development of ophthalmic instrumentation equipped with AO, with commercialization as the goal. Broad commercial accessibility requires the development of low-cost, compact, and robust devices that can be used by clinicians who are unskilled in adaptive optics. There is mounting evidence of the scientific value of adaptive optics for the eye. Its ability to aid in the diagnosis and or treatment of retinal disease is now being explored at all the participating institutions in this Theme.

2.2.3.2 Instrumentation

2.2.3.2.1 Houston Adaptive Optics Scanning Laser Ophthalmoscope
The decision to build the adaptive optics scanning laser ophthalmoscope (AO-SLO) at the University of Houston was part of an effort by the CFAO to expand the scope and functionality of AO-based ophthalmic systems. An SLO does not take a snapshot of the retina. Rather, it constructs an image over time by measuring the scattered light from a focused spot on the retina as it scans across it in a raster pattern. This imaging modality confers several advantages that go beyond retinal imaging. Applications include axial sectioning of the retina, retinal tracking with high speed and unprecedented accuracy, and simultaneous retinal stimulus delivery and imaging (for perimetry or psychophysical testing).

Although the AOSLO was completed in 2001, many technical challenges still need to be overcome before all the benefits of this imaging modality are realized. In Year 5 advances were made in the areas of AO control, laser light delivery, and effects of light sources on system performance.

AO control. We recently adopted a zonal, or direct-slope based approach to closing the loop in the AO system. With the zonal method, the exact responses of the deformable mirror are measured (influence functions) and the voltages that are required to flatten the mirror are computed directly from the slopes measured on the wavefront sensor. While this is standard practice in most AO systems, it represents a major step in the AOSLO lab. Until now, we have used a two-step modal approach, where the wavefront is first fitted with a Zernike polynomial and the voltages are then calculated from the best fitting wavefront. Future tests will indicate which approach is better. Under some conditions, for example when there are some poorly located centroids due to cataract, the low-pass filtering of the Zernike fit may be advantageous. The AOSLO offers a unique method to compare the two AO control methods for retinal applications. Last year we showed that in the confocal imaging mode, relative changes in intensity of the AOSLO images are directly proportional to the Strehl ratio of the AO system. Thus, we can compare the two reconstruction methods simply by comparing the average brightness of the images (this test is planned for sometime this summer). Normally, determining the Strehl ratio from retinal images is difficult since the retina is an extended object and no isolated point sources are available. The relationship between relative image intensity and Strehl ratio is also being used to investigate the effects of tear film on image quality. Tear film causes aberrations, most of which are too high to be measured with a Shack-Hartmann wavefront sensor.
Laser Light Delivery. The light delivery path in the AOSLO is a point laser source, which is scanned in a raster by two mirrors, and focused onto the retina. Until now, we have used an analog circuit to switch the laser on and off as required. In Year 5 we developed a new system for laser light delivery, comprising a high frequency wavefunction generator D/A board coupled with an acousto-optic modulator. By synchronizing the laser control with the scanning mirrors, we are now able to project any complex spatial pattern onto the raster. In other words, we can write pictures directly onto the retina. Moreover, these images, when written onto the retina, can also be seen on the retinal image that is being recorded. This new feature combines the ability to deliver AO-corrected stimuli (since the aberrations are corrected on the way in as well as on the way out of the eye) with an unprecedented ability to measure exactly where that stimulus has landed. Figure 2.29 shows a single frame retinal image containing the stimulus. Note that the stimulus is not an overlay, it is part of the image itself.

AOSLO Light Sources. Whenever coherent sources are used in an AOSLO, speckle and interference between cones will cause noise and artifacts in the retina images. To test the extent to which this affects the images, we compared images taken with our current laser diode, with those taken with a low-coherent, superluminescent diode. The system was aligned so as to enable easy switching between the two sources. We found that while the contrast was higher with the laser diode, the superluminescent diode produced retinal images with fewer artifacts. In other words, the high contrast from the laser diode was mostly artifact and served to mask the retinal details rather than reveal them. Figure 2.30 shows retinal images of the same eye taken with each laser. The insets are the Fourier Transforms (FFTs) of the photoreceptor mosaic. The FFT from the superluminescent diode image shows a much cleaner frequency signal from the photoreceptors then does the image taken with the coherent laser. (When you have a contiguous, quasi-amorphous packing arrangement of cones, then the FFT should appear as a distinct ring near the sampling frequency. This is called Yellott’s ring.) This is an important result and has motivated our group to purchase a new superluminescent diode for use in the AOSLO system.
Figure 2.30 The image on the left is taken with a low coherent superluminescent diode. The image on the right is taken with a highly coherent diode laser. The left image shows a more contiguous photoreceptor array. This is also evident by the smoothness of circularity of the ring in the FFT. The higher apparent contrast of the cones in the right image are an artifact caused by speckle and interference between cones.

2.2.3.2.2 The Indiana Coherence Gated Retinal Camera

The objective of this project is to develop a bench top adaptive optics (AO) camera that incorporates optical coherence tomography (OCT) for microscopic imaging of the living human retina. The high transverse resolution obtained with AO complements the high-axial resolution of OCT and together provide a powerful imaging tool whose 3-D resolution can substantially surpass that of either methodology alone. The point spread volume of the Indiana AO-OCT camera is currently 234 mm$^3$, the smallest of any reported retina camera.

In year five, substantial progress was made on several engineering fronts, many of which were accelerated by Center collaborations. These include the following: (1) Eye motion artifacts were substantially reduced through improvements in camera efficiency and OCT reconstruction algorithms. (2) Two speckle reduction approaches were pursued, motivated by the high level of speckle noise observed in the AO-OCT retinal images. One approach involved significant collaboration with Thomas Milner (Elect. Eng., Univ. Texas) and resulted in a SPIE conference presentation and a manuscript currently in preparation. (3) The AO system was extensively overhauled in search of a sporadic, yet troubling, temporal instability that manifested itself when the AO loop was closed and which diluted the AO benefit. Indiana received considerable assistance from astronomical Center members on this persistent AO problem including CfAO, LLNL) and Julian Christou (CfAO, UC-Santa Cruz). Marcos van Dam’s visit was supported by a CfAO Mini Grant and nicely demonstrated the benefit that can germinate through interdisciplinary collaboration. (4) Christou’s visit initiated a collaborative deconvolution project that will continue in Year 6. The deconvolution project had been postponed due to the unstable AO, which prevented the acquisition of data appropriate for deconvolution. (5) The high speed conventional AO camera was successfully used to provide the first reported objective, non-invasive mapping of the capillary bed that forms the foveal avascular zone. Images were compared to those obtained with a commercial flood-illuminated camera.
(Topcon-50EX) and entoptic drawings made on the same eye. Results from the three methodologies are shown in Figure 2.31, which exquisitely reveals the subtle capillary details captured with AO, but undetected with the other two methods. (6) This experiment was followed by improvements in the camera control software that increased the continuous frame rate to 9.5, 23, and 30 Hz for imaging 1.8, 1, and 0.8 deg retinal patches, respectively. The 23 Hz rate is a factor of six higher than that reported in the Year 4 Annual Report for the same field size and number of field pixels. Results were presented at the 2004 SPIE Photonics West and ARVO meetings.

![Figure 2.31](image)

**Figure 2.31** The retinal capillary pattern surrounding the foveal center in the same subject as assessed by three different non-invasive techniques: (a) photograph from a Topcon-50EX commercial camera, (b) spatial distribution of vessels as determined from images collected with the AO camera, and (c) entoptic drawing based on observations.

In Year 6, focus will be divided between camera development and vision science. Indiana will build on prior successes, while pursuing a new OCT direction. The AO-OCT camera, completed in Year 5, met essentially all of the original design specifications, in some cases exceeding them. However, unexpectedly large amounts of speckle noise, sensitivity to micro-movements of the eye, and technical complexities of parallel OCT were persistent problems that ultimately dampened enthusiasm for flood-illumination OCT. Concurrently, other forms of OCT (in particular spectral OCT and en face scanning OCT) have rapidly matured in the last few years and now justify a re-evaluation of our approach. Year 6 milestones include 1) rigorous calibration of the AO system, 2) mapping the foveal microvasculature in several normal and pathologic eyes, 3) deconvolution of retinal images, and 4) experimental evaluation of spectral OCT using the current AO-OCT camera. Collaboration with engineering expertise both in and outside the Center will continue in Year 6. Explicit engineering collaborations include projects with Julian Christou, Thomas Milner, and Marcos van Dam. Other collaborators include Scot Olivier (LLNL), Joseph Izatt (Biomedical Eng., Duke), and Jack Werner (Ophthalmology, UC-Davis). Vision collaborations with Austin Roorda (Houston) and David Williams (Rochester) will continue. The high-speed AO retina camera is ready for use by the broad
vision community. A multi-year National Eye Institute grant was awarded and will accelerate, but not overlap, developments in the new OCT direction.

2.2.3.2.3 MEMS AO Phoropter
This project is a collaboration between the University of Rochester, Lawrence Livermore National Laboratories, Sandia National Laboratories, Wavefront Sciences, Boston Micromachines, and Bausch & Lomb to develop a portable adaptive optics phoropter, suitable for clinical demonstrations. During CfAO Year 4, this instrument was moved to the University of Rochester for final assembly and preliminary tests on human eyes, with the intention of transferring it to Bausch & Lomb at a later date, in Year 5, for more extensive clinical studies. During the preliminary tests of the MEMS AO Phoropter (MAOP) in March 2003, several key areas for improvement were identified: 1) the subject interface, 2) the user interface, and 3) the physical housing for the instrument. These were addressed through software upgrades and hardware improvements, including the machining of a new housing for the MAOP. As a result of these improvements, more extensive tests on human subjects were performed during Fall 2003. However, while the results of these psychophysical tests showed qualitatively that the instrument was capable of correcting small amounts of aberration in human eyes, the amount of improvement was too small to be measured quantitatively. Thus, additional improvements for the MAOP were identified – such as the replacement of the deformable mirror with a higher-stroke mirror – and work on these areas has extended into CfAO Year 5. This has delayed the delivery of the MAOP to Bausch & Lomb. However, the MAOP will be ready for clinical studies by the end of Year 5. We have had discussions with several potential corporate partners including Reichert and Carl Zeiss Meditec.

2.2.3.3 Image Processing

2.2.3.3.1 Improved software tools for retinal image analysis.
Over the past few years, CfAO vision science instruments have produced thousands of retinal images. Unfortunately improving the process of image analysis has not been a primary objective, and as a result it remains time-consuming. The time required varies depending on the particular imaging project (e.g. imaging diseased retinas, cone classification, imaging the dichromatic retina). But on average, for every hour of retinal imaging, it takes between 3-5 hours of image processing to extract quantitative data from the images. As the number of images generated is increasing, a strong focus for Year 6 at U. Rochester will be to develop new software tools for retinal image analysis. Gang Pan, Julianna Lin, Joseph Carroll and Sapna Shroff at Rochester will be involved in this effort, the results of which are already being shared at a number of sites. A brief outline of the tools under development is given below:

Rapid Image Registration Software. It is necessary to register multiple images from the same retinal location in order to produce an image of high contrast and to resolve fine spatial structures. This process is by far the rate-limiting step in image analysis. Gang Pan is exploring alternatives to our current slow and inefficient method of image registration. Some of these improvements include the use of more efficient data structures, better use of memory (e.g. batch processing), and faster algorithms for calculating the correlation coefficients between images. Experience of the astronomers in registering images will be incorporated into our new processes.
**Improved Deconvolution of Retinal Images.** Julian Christou has demonstrated the potential benefits of applying deconvolution technology for improving retinal image contrast. A graduate student, Sapna Shroff, supervised by David Williams and James Feinup, will be working on this project. She will be actively involved in implementing practical deconvolution algorithms as well as investigating other post-processing operations for improving image contrast. The methods developed by Julian Christou will be improved and other methods of deconvolution and image estimation will be explored.

**Automated Montaging Methods.** Single images from the Rochester Adaptive Optics System are approximately 1 degree in diameter. In order to make comparisons across the retina, it is necessary to get a larger view of the retinal cone mosaic. Images from multiple neighboring retinal locations are merged to form a single, larger image. A single montage of about 3.5 degrees field of view requires between 20 and 45 retinal locations. Currently, this is done manually in Adobe Photoshop, requiring many hours of tedious aligning, filtering and image transformation. Rochester will develop a MATLAB program to take images from many retinal locations and automatically form a montage image. Experience of the astronomers in registering images will be incorporated into our new processes.

**Improved Automated Cone Identification Algorithm.** From these large montages, one can calculate cone density as a function of eccentricity in the retinal cone mosaic. To do this, it is necessary to identify the (x,y) coordinates of all the cones in the montage, which is upwards of 15,000 cones. This is currently done manually using a software package called Image J and requires days of scanning the image and clicking on each cone with a mouse. Rochester will develop additional software in Year 6 that will largely automate this process.

**Image Dewarping:** Two types of image distortion are present in the images from a scanning laser ophthalmoscope. The first are constant distortions due to non-linearities in the scanning mirrors. We have developed software to exactly remove this distortion from every frame in our movie sequences. Since the exact nature of the static warp depends on the field size, we have built a calibration “model eye” with a grid in place of the retina. We then use custom software to analyze the calibration image and generate a unique distortion correction for each imaging session.

A second AOSLO retinal image distortion is caused by eye movements. In an SLO, the image is constructed over time as the focused spot scans in a raster pattern across the retina. During that time the retina is constantly moving, which causes each frame to be distorted. Figure 2.32 shows a sequence of three images. During the acquisition of the central frame, the eye made a saccade to the left, giving rise to the distortion that is seen. In the third frame, the image of the vessel pattern reassumes the shape seen in frame one. Eye movements have a wide range of frequencies, amplitudes and directions and are constantly present, so every frame is distorted in a unique way. This distortion imposes a major limit on the ability to register frames, which is a necessary step for increasing the signal to noise beyond that of static single frame retinal images. The distortions do not allow for the traditional shift-and-add methods that are ubiquitous in image processing. We have adopted a two-level approach to solving this problem. The first is to do a selective shift-and-add to register only the subset of frames that have undergone the least
distortion. The most recent version of the software (written by Krishnakumar Venkateswaran) scours through a video sequence and selects the ones that register best with a template frame. Figure 22.33 shows a selection of registered frames using the new registration software.

Figure 2.32: Sequence of three frames showing image distortion due to eye movements.

Figure 2.33 Registered images of the photoreceptor mosaic in three different eyes using our second generation registration algorithms.

The second, more ambitious, approach is to analyze each image to undo the distortion caused by eye-movements. There is a double benefit from this approach. First, it makes use of all the frames and will yield excellent signal to noise in static frames. The second benefit is that one obtains a high frequency trace of eye movements with unprecedented accuracy. This project was initiated by Mark Campanelli, a math graduate student of Curt Vogel at the University of Montana who worked in Roorda lab in Houston on a CFAO mini-grant in 2003. We have since stepped up efforts to get a useable product, supported by both CfAO and a National Institute of Health grant. The project team includes Curt Vogel, David Arathorn and Derek Sonderegger from the University of Montana, who are experts in solving inverse problems. Scott Stevenson and Austin Roorda from the University of Houston complete the team. Scott Stevenson is an expert in eye movements. Specific CfAO funding is slated for Year 6 of the grant, but preliminary work is already underway.
2.2.3.4 MEMS Deformable Mirror Development
In Year 5, CfAO supported three efforts to develop low cost, compact, high stroke MEMS deformable mirrors for Vision Science. This development effort is essential to meet our goal of commercializing adaptive optics technology in ophthalmic applications.

2.2.3.4.1 Boston Micromachines Corporation
Boston Micromachines Corporation makes deformable mirrors (DMs) for adaptive optics systems. They are fabricated using microelectromechanical systems (MEMS) technology and are similar in size to the eye’s pupil. These DMs with their current stroke have proved capable of correcting a limited range of aberrations sufficient to improve retinal image quality. Boston Micromachines Corporation’s MEMS-DMs have been used, for example, at the University of Rochester in a fundus camera with adaptive optics. While the experiments produced promising results, the MEMS-DMs had insufficient range of motion (~2µm stroke) to permit full correction of aberrations of the eye of a normal range of human subjects. Other retinal imaging systems developed to date with MEMS-DMs suffer similar limitations. What is needed is a MEMS-DM device with significantly extended actuator stroke.

The Year 5, research focused on further extending the range of travel by optimizing the actuator design and increasing the actuator gap. The deformable mirror actuators produced to date by Boston Micromachines Corporation used an electrostatic actuator gap of 5µm, because that is the thickest sacrificial oxide layer that can be deposited, patterned, and etched successfully at a commercial silicon MEMS foundry. If the sacrificial oxide layer could be increased in thickness, the stable actuator stroke could be extended in direct proportion to that increase. The primary difficulty encountered with thick films is etching the straight narrow channels required for actuator anchor attachments. In Year 5, extended stroke actuation was demonstrated: a large electrostatic actuator gap was created by combining two sacrificial oxide layers with an interstitial silicon layer. Each of the two oxide layers used in the stack was 5µm thick, making etch processes tenable at the silicon foundry. To limit peak required actuator voltage, this test actuator was manufactured with a span more than twice as large as normal, its electrodes were split, and its membrane was perforated to reduce mechanical restoring forces. With this device, actuator mid-span stroke of nearly 6µm was achieved. Figure 2.34 shows a schematic of the device and its measured mid-span deflection as a function of applied voltage.

![Figure 2.34](image)

**Figure 2.34** Measured mid-span deflection as a function of applied voltage for large-gap actuator with split electrodes. With a 10µm gap, stable deflection of up to 6µm (60% of the gap) was achieved.
Although this prototype demonstrated long stroke, the stacked oxide layer approach cannot be used for actuators in MEMS deformable mirror fabrication. The interstitial silicon layer would introduce micrometer-scale non-flatness in the mirror membrane. Hence work was performed to identify an alternative etching process suitable for the double-thick (10µm) sacrificial layer, eliminating the need for an interstitial silicon layer and two sacrificial oxide layers beneath the actuator membrane.

Devices were designed and modeled using a 7µm actuator gap such that the resulting stroke would exceed 4µm. The new devices also utilize the split electrodes and actuator cuts developed previously. In a trial etching experiment, a 7µm thick layer of oxide was deposited and etched by MEMSCAP, the MEMS foundry that is currently used for silicon micromachining of Boston Micromachines Corporation optical MEMS products. The results indicate that thicker oxide layers can be etched successfully. The first evaluation wafer from the fabrication run that includes the new designs and the thick oxide layer was received in July 2004 (Figure 2.35). It is being evaluated in the summer of Year 5.

The aim of the Year 6 program is to design, fabricate and test actuator arrays to demonstrate the feasibility of MEMS-DMs having 6 µm of stroke. The baseline design for the long-stroke actuators will incorporate modified actuator geometries similar to those previously fabricated by the project team. Actuator designs will include a 10 µm electrostatic gap, split-electrodes, extended actuator span, and membrane perforations to increase actuator compliance. A new design feature will be the inclusion of an insulating silicon nitride layer over the actuator’s fixed electrode, preventing damage when the device is subjected to over-voltage conditions which have been found to be the leading cause of failure in the current silicon MEMS DMs produced by BMC. Table 1 lists the expected characteristics of these actuator arrays.

Preliminary analysis has shown that these goals are achievable. Figure 2.36 shows results of a finite element simulation of one combination of the actuator geometric features (410µm span, 180µm wide split electrodes, perforated membrane) with a 10µm gap which achieves a 6µm deflection at ~190V. MEMS-DM actuator fabrication will employ a special short-loop option at the silicon foundry. A short-loop enables fabrication of small batches of wafers on a relatively rapid schedule. The custom short-loop fabrication process uses two structural layers of...
polysilicon (poly) alternating with a sacrificial layer of phosphosilicate glass (PSG), or oxide.

<table>
<thead>
<tr>
<th>Table 1. Expected Phase I Actuator Array Characteristics</th>
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<tbody>
<tr>
<td>Actuator pitch</td>
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<tr>
<td>Actuator stroke</td>
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<tr>
<td>Maximum actuation voltage</td>
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<tr>
<td>Aperture (140 element array)</td>
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After the actuator arrays have been fabricated, tests will be performed to evaluate the yield, electro-mechanical characteristics, and stress state of the devices. Yield will be first determined by optical inspection using a high power optical microscope. Each individual chip will be examined for contamination, lithographic errors, or defects due to mishandling during fabrication.

2.2.3.4.2. IrisAO

Iris AO, a spinoff company of the CfAO and the UC Berkeley Electrical Engineering Department, has been working on a MEMS mirror architecture specifically designed for the high-stroke requirements of vision science and extremely large telescopes. In December, 2003 Iris AO requested the CfAO to reallocate funds from driver electronics construction to outsourcing DM fabrication to Fairchild Semiconductor Corporation (FSC). Considerable processing variability had been observed when using the non-dedicated, academic facilities available at the UC Berkeley Microfabrication Laboratory (Microlab). Transferring activities to a commercial foundry service would resolve many of process control problems that had been experienced. In addition Iris AO recruited Dr. Thor Juneau to do DM design and layout and Dr. Matthew Hart to perform the characterization and optical testing of the processed wafers. These key hires have enabled the company to employ a more thorough and rigorous approach to planning, designing and testing for the first FSC foundry run.

2.2.3.4.2.1 Year 5 Progress

1) **Failure Modes Effects Analysis (FMEA).** A thorough analysis of the MEMS DM design has identified and classified many of the possible failure modes. Iris AO met with a CfAO technical assessment team in February 2004 to discuss design improvements and assess the optimum technology path.

2) **Short-loop Design and Testing.** Based on results from the first DM run in the Microlab and the results of the FMEA analysis, Iris AO devised an extensive series of “short-loop” tests to further refine working processes, refine the first DM design, and test critical failure modes before incurring the time and monetary costs of a full foundry run. Most of the short-loop tests for individual process steps are completed as of July 2004. A more robust design has emerged with less process variation. Short-loop tests to determine the effects that could result after integration of the individual process steps have begun and are scheduled to be completed by September 2004.

3) **Commercial Foundry Service:** FSC will perform processing of the wiring, electrode and starting material layers. FSC engineers are working closely with Iris AO to ensure that the submitted designs conform to their established SUMMiT IV methodology.

4) **Completion of First Generation Design:** Final “tape out” of the 1st generation FSC designs was completed in May 2004.
5) **Actuator-Wafer Fabrication:** Actuator wafers fabricated at FSC are scheduled to arrive at Iris AO by the end of July 2004. Preliminary electrical testing of the FSC wafers will commence on delivery. After successful testing, deposition and patterning of the bimorph layer and metallization will begin.

6) **Mirror Wafer Fabrication:** Short loop testing for the mirror wafers will be completed by the end of July 2004. Fabrication for the mirror wafers will be completed by the end of August 2004.

### 2.2.3.4.2.2 Timetable for 1st Generation DM using FSC Actuator Wafers

- Provide initial data on actuators performance: August to October 2004
- Mirror wafer processing complete: August 2004
- Post processing of actuators compete: September 2004
- Assembly of mirror chips onto actuator chips: October 2004
- DM prototypes ready for internal testing: November 2004
- DM prototypes delivery: December 2004

### 2.2.3.4.3 MEMX, Inc.

CfAO funding for MEMX began midway through Year 5. The objective of the MEMX research program is to improve the flatness of SUMMiT V MEMS mirrors by minimizing packaging-induced degradation in mirror flatness and by optimizing processes for sputtered and evaporated metals. The research program is split into 3 distinct tasks:

**Task 1.** Optimize the MEMX packaging process to minimize packaging-induced degradation of mirror ROC.

**Task 2.** Optimize the deposition of evaporated metals on SUMMiT V mirrors. The following variables will be optimized — ion beam current, ion beam voltage, and the composition of the adhesion layer in the metal stack will be tweaked while remaining compatible with the pre-release processing. The deliverable of this task will be the specification of a low stress metal stack to maximize mirror ROC.

**Task 3.** Optimize the deposition of sputtered metals on SUMMiT V mirrors. The goal is to optimize the variables of adhesion layer thickness, adhesion layer composition, processing pressure, and sputtering energy. The deliverable of this task will be the specification of a low stress metal stack to maximize mirror ROC.

Work began on this research program in June 2004 under the leadership of Principal Investigator Dr. Jeffry Sniegowski.

### 2.2.3.5 Testing MEMS Mirrors in the Rochester Test Bed.

Over the past year, the University of Rochester has had access to two adaptive optics systems for vision science: 1) the Rochester AO Ophthalmoscope, and 2) the MEMS-based AO Phoropter (MAOP) system, built in collaboration with Lawrence Livermore National Laboratories, Sandia National Laboratories, Wavefront Sciences, Boston Micromachines Corporation (BMC), and Bausch & Lomb. Since either system can be used to test alternative forms of wavefront correction such as high-stroke MEMS mirrors, the MAOP was chosen to test the latest set of high-stroke MEMS mirrors produced by BMC. The mirrors from this production run are very similar to that purchased for the initial design of the MAOP, but have twice the amount of stroke and much smoother reflective surfaces. Although the preliminary set-up of a new mirror in late January looked promising, a manufacturing flaw was soon discovered and testing on that particular mirror was terminated. A second mirror was delivered for testing in March 2004, but
concerns about the control electronics caused an additional delay. With the arrival of new
electronics in early April, tests on the new high-stroke MEMS mirror from BMC were
conducted that demonstrated all 120 actuators were functioning normally. The mirror has
behaved flawlessly for the past month, which is exciting news for the future for MEMS-
based AO systems for vision science. The stroke is not as high as required, but new
designs promise further improvement.

Segmented mirrors have yet to be characterized for correcting the eye’s
aberrations. We anticipate mirror manufacturers will do this and provide implementation
data to the instrument developer. To increase efficiency in testing, Rochester will build a
removable testing insert capable of accepting a wide array of MEMS mirrors. This insert
will fit into the Rochester AO system without disturbing the other imaging components.
Testing a wide range of MEMS mirrors will require that the AO system be re-optimized.
This may require a new wavefront sensor configuration, and new software development.
Rochester will develop a list of key specifications for MEMS mirrors used in visual
systems so that future mirrors can be more easily evaluated. The results obtained with the
Rochester test bed will guide the choice of mirror design for future instruments built at a
number of sites. These include Houston, Indiana, LLNL, UC, Davis, Schepens Eye
Research Institute, as well as Rochester. Ultimately, these mirrors will be deployed in
commercial AO instruments developed through corporate partnerships with CfAO. This
work has broader applicability outside of CfAO due to the new ophthalmic instruments
being built as part of the two NIH Bioengineering Research Partnerships.

2.2.3.6 Scientific Achievements

Scientific milestones associated with projects funded by sources other than CfAO.
CfAO support at Rochester, maintains the adaptive optics technology expertise, necessary
to perform these experiments.

2.2.3.6.1 The packing arrangement of S, M, and L cones outside the fovea.
One of the more exciting results from the Rochester group has been the revelation that the
relative numbers of S, M, and L cones vary dramatically across individuals with normal
color vision. Pilot data from Heidi Hofer has shown that within a subject, the relative
numbers of L and M cones measured with adaptive optics can vary with retinal location.
Shown in Fig. 2.37 are 2 pseudocolor images from the same eye, but at different locations.
S, M and L cones are labeled as blue, green and red, respectively. The estimated L:M
ratio (expressed as %L cones) is ~55%L for the Nasal patch and ~65%L for the temporal
patch.

![AP temporal](image1)
![AP nasal](image2)

Fig. 2.37  Variation of L and M cones with Retinal locaiton

Thus one of the goals for Year 5 was to determine how representative a single estimate of
L:M ratio from adaptive optics was of the L:M ratio across the retina. For 8 subjects we
compared L:M measured with the adaptive optics to that estimated from a large field (70
degrees) electroretinogram paradigm. A high correlation was found between the two techniques, which suggests that a single estimate of L:M ratio from adaptive optics will be close to the L:M ratio for the entire central retina, though this needs to be tested further. The group also wanted to measure the organization of the 3 cone classes at different retinal eccentricities. It is known that during development, the cone photoreceptors migrate towards the fovea. Estimates of the organization of the cone types might not be true of the entire retina (though the relative numbers of the different cone types may indeed remain constant). In the first attempts to classify the 3 cone types at these locations, the decrease in the amount of photopigment in the individual cones makes the bleaching levels even more critical. The Rochester group is now working on improving the bleaching set-up and expect to soon be able to probe the organization of the 3 cone types in these peripheral locations.

2.2.3.6.2 The cone mosaic of color blind eyes.
Dichromatic color vision results from the functional loss of one cone class. However one of the central questions has been whether individuals with this form of red-green color-blindness have lost one population of cones or whether they have normal numbers of cones filled with either of two instead of three pigments. Evidence has accumulated favoring the latter view in which the photopigment in one class of cone is replaced, but the issue has not been resolved directly. The Rochester group obtained images from 2 dichromats, one of which showed a remarkable physical loss of cones in his retina (the other dichromat had a normal-appearing mosaic). Images from these 2 subjects are shown in Fig. 2.38. The images are from the same retinal eccentricity, about 1 degree in the temporal direction. The image on the right (NC) is from a dichromat who has a novel mutation in one of his cone visual pigment genes, resulting in the loss of the corresponding cone class. The subject on the left (MM) is simply missing the gene for one of his cone visual pigments, and his mosaic is normal in appearance. This finding suggested that previous model of dichromacy does not hold for all subjects.

During Year 5, retinal images from an additional 11 dichromats were obtained using the Rochester Adaptive Optics System. Blood samples were shipped from each subject to Dr. Maureen Neitz at the Medical College of Wisconsin. She is able to extract DNA from these samples and determine the precise genetic cause for each subject’s color blindness. We have enhanced our ability to rapidly analyze cone density in the retinal images obtained. This work has been published in the Proceedings of the National Academy of Sciences. On going work will be aimed at establishing a firm model whereby one can predict the retinal phenotype from knowledge of the genotype. Such a model would lay
2.2.3.6.3 Cone Mosaics of Heterozygous Carriers of Color Vision Defects.
About 14% of females are carriers of an X-linked color vision defect, though their color vision appears normal. This means that they have one X-encoded photopigment gene array that is able to express functional L and M pigments and one X-encoded photopigment gene array that can express either only the L- or only the M-pigment gene. Heterozygous carriers of red-green color vision defects are expected, if random X-inactivation is assumed, to have highly skewed L:M cone ratios. This is because the presence of a deutan or protan array, in addition to a single normal array, restricts the possible range of cone ratios in female carriers. For example, whereas very few normal males have fewer than 50% L cones, protan carriers on average can have no more than 50% L cones – for even if their normal gene array was producing L-cone pigment 100% of the time, the pigment produced by the normal array is only present in half of the L/M cones, resulting in an effective maximum of only 50% L cones. Of course, in the rare instances where X-inactivation is skewed, there is the potential for a protan carrier to have more than 50%L cones. The enduring view in the literature is that this skew in L:M ratio among heterozygous carriers somehow diminishes their color vision capacity. This has often been attributed to the creation of a mottled retina via X-inactivation, where patches of “normal” (L- and M-cone containing) and “colorblind” (L- or M- cone containing) retina are believed to exist. However, recent work from the Rochester group has identified a normal male with an L:M ratio even more extreme than those of female carriers but having normal color discrimination. This would seem to be in contradiction with previous studies. Is there perhaps something different about the “colorblind” cones in the retina of the carrier that causes them to not function properly? Or, will further examination of these abnormal males show that they too have compromised color vision? Or, will direct examination of the heterozygous retina with adaptive optics show that they do not have patchy retinal mosaics? Part of the answer lies in determining just how different the L:M mosaic of female carriers is compared to those of males (both those with normal and abnormal L:M ratios). One difficulty is that in carriers, there is no practical way to identify L and M cones derived from a “normal” X-chromosome photopigment gene array and those coming from a “colorblind” gene array. However, due to the nature of the inheritance of red/green color vision defects, there exist females who are carriers of both protan and deutan color vision defects. This allows us to disambiguate the contribution of the 2 X-chromosomes to the organization of the cone mosaic. Thus for the first time, it will be possible to isolate the degree to which X-inactivation influences the arrangement of the human L/M cone mosaic.

2.2.3.6.4 The Effect of Wavelength on Photoreceptor Images.
The reflectance of human retina increases dramatically with increasing wavelength. At the same time, longer wavelength light penetrates deeper into the retina, which means the light gets scattered more by deeper layers such as choroid. The prevailing view is that light traversing the receptor layer from deep layers does not get coupled efficiently into cones. Therefore, one would expect the contrast of the imaged cone mosaic to decrease with increase in wavelength. However, retinal images obtained by the Rochester group did not reflect this. Images taken with longer wavelength were nearly as high contrast as those taken with shorter wavelength. Images were obtained at three wavelengths, 550, 650 and 750 nm (Figure 2.39).
Overall, the power spectrum plots from different wavelengths looked very similar to each other. There was a slight degradation of contrast in power spectrum plots with increase in wavelength, but the magnitude of this variation was much smaller than the value expected from previous studies and models. These results must imply that a large portion of light from choroid is coupled back into the receptors, contrary to earlier predictions.

Fig. 2.39 Relating Retinal imaging to wavelength of light used.

**2.2.3.6.5 First Images of Rods in the Living Human Eye.**

By increasing the transverse and axial resolution of retinal imaging systems, adaptive optics (AO) has allowed for the routine *in vivo* imaging of the cone photoreceptors. Our goal was to see if this imaging modality could be extended to allow for visualization of the *rod* photoreceptors, which are substantially smaller in diameter. Deconvolution, performed by Julian Christou, was used to enhance the image contrast of the registered images. With a 6.8mm pupil diameter, small structures were observed in between the larger cones. The rod and cone spacing from the retinal images agreed favorably with that of reported histology data, i.e. cone spacing is about 4-5 times the rod spacing. Moreover, the rod center to center spacing should not change with increasing eccentricity and this was found to be true; at the same time, the cone frequency decreased with increasing
Fig. 2.40 Deconvolution techniques used on retinal images reveal rod-like structures.

eccentricity. The same structures at the same location were seen repeatedly, indicating that there is structure that is independent of noise. Collectively, all our results support the notion that there are small structures between the cones in our images, and they have very comparable properties to that of rods. Rods have a sampling frequency of around 120 c/deg, which is very close to the cut off frequency of our system. This has an important implication clinically, since it will help us understand the possible mechanisms of various retinal diseases that either mainly affect rods or affect rods first and subsequently cones.

### 2.2.3.6.6 The Time Course of Neural Compensation for the Eye's PSF.

In collaboration with Pablo Artal’s laboratory at the University of Murcia, the Rochester group showed that the neural system can compensate for defects in the eye’s optics\(^\dagger\). In Year 5, additional experiments were conducted using adaptive optics to explore the temporal dependence of this adaptation process. Visual acuity was measured in subjects in white light, while the subjects view the stimulus through the adaptive optics system with their own aberrations, with the rotated version of their aberrations, or with their wave aberrations removed by adaptive optics. Accommodation was paralysed and a 6 mm pupil size was used during the measurements. In every subject the RMS wavefront error of the rotated aberrations was similar to the normal one. High contrast visual acuity (VA) was measured before and after periods of continuous adaptation to the rotated version of the aberrations.

aberrations. The average VA (expressed as the minimum angle of resolution (MAR) in minutes of arc) in the three subjects for their normal aberrations was 1.0. However, with the ocular aberrations rotated 45 degrees, VA increased to 1.55, indicating a significant reduction in visual acuity. After 15 minutes of continuous viewing through the rotated aberrations, VA improved to an average value of 1.16. This represents a recovery of nearly 50% of the normal acuity level. Longer temporal periods of 25 minutes were also considered in one subject, showing a slightly higher recovery of acuity. A similar general behaviour was obtained when we measured low contrast VA and blur matching in both monochromatic and polychromatic light. These results further support the hypothesis that the neural visual system compensates for the eye’s particular aberrations. Visual acuity is significantly reduced when measured with a rotated aberration pattern. We also found that this adaptation is partially reversed in a relatively short time of 15 minutes. These results may have important implications for understanding the impact of aberrations on different aspects of clinical vision, and could play a role in improving refractive procedures.

These experiments leave unanswered the question of whether neural factors influence the pattern of aberrations that optimizes subjective image quality. In other words, does the world look sharpest when all aberrations are corrected, or when aberrations remain that are present in normal viewing? The University of Rochester plans to investigate this question by providing subjects with control of the amount of aberrations in their eyes, from their normal pattern to one in which most aberrations are corrected with AO. Subjects will have continuous control of the amount of aberrations in their eyes and will set the amount to optimize their own subjective image quality.

2.2.3.6.7 Perceived Retinal Motion with AOSLO Psychophysics Module.

Scott Stevenson, Siddharth Poonja, Avesh Raghunandan and Austin Roorda have completed a series of preliminary experiments to test whether the perceived direction of motion of a dark bar in the retinal image is based on its absolute motion on the retina, or the motion of the bar relative to the edges of the raster pattern. The experiment involved the presentation of a sequence of AOSLO frames to the retina. Two of the frames contained a dark bar, the second of which was displaced slightly above or below the first. The subject’s task was to judge whether the bar moved up or down. The ability to do this correctly depends on how far the bar moves, and how much time delay there is between the presentation of the first and second bar. In the time delay between the presentation of the first and second bar, the eye moves due to normal fixational jitter. In some cases, even though the bar has moved down, the eye might have moved down further causing the actual location of the bar on the retina to move up. The actual location of the bar on the retina could be determined to within a single cone, since the stimulus was contained in the AOSLO retinal image. Our hypothesis - that the sensitivity to small movements of the bar would be improved if we considered actual retinal movement of the bar rather than the movement of the bar relative to the frame - failed. We analyzed subject responses to bar motion with respect to the frame and to the retina, and responses were consistent with frame motion despite substantial fixational jitter. This result indicated that the eye judges the motion of objects based on how they move relative to their environment and not on how they move on the retina. Figure 2.41 shows one example of a pair of images where, although the bar has moved down, the retina has moved down farther causing the actual motion of the dark bar on the retina to be upward. Under most conditions like the one shown here, the subject judged the motion of the bar to be downward. More studies, which investigate unreferenced retinal motion, are underway and are planned for Year 6.
2.2.3.6.8 AO retinal imaging in retinal disease.

One goal for the CfAO is to implement adaptive optics imaging systems in the clinical setting for assessment and early diagnosis of retinal disease. Diseases of interest include age-related macular degeneration, glaucoma, diabetic retinopathy, retinitis pigmentosa, achromatopsia, and cone-rod dystrophy. In the Rochester Adaptive Optics System, data collection is limited to subjects with clear optical media, i.e. young subjects. Most retinal disease patients are elderly, making imaging on these subjects difficult. As well, many retinal disease patients have a hard time maintaining fixation. For these two reasons, the Rochester group has concentrated on identifying, recruiting, and imaging young patients with stable fixation for these studies. Through collaboration with Irene Maumenee at Johns Hopkins University, a subject with achromatopsia was imaged using the Rochester Adaptive Optics system. Achromatopsia is a group of disorders where color vision is either entirely absent or severely defective. Psychophysical measurement supports the idea that there is no sensitivity from the cone photopigments in these patients. Patients with the classical form of achromatopsia have an autosomal recessive genetic mutation. The genetic mutation for our patient, RM, was well documented as Ser322Phe. This specific mutation allows the phototransduction channels to form properly in the photoreceptors, but these channels are unable to close when light is incident on the photoreceptors. This slight mutation completely prohibits the photoreceptors from sending a visual signal through the cone phototransduction channel. The images obtained of RM’s retina with the Rochester Adaptive Optics system are the first in vivo images of achromatopsia. One image is shown in Fig. 2.42. The images obtained raise several issues regarding the disease. First, are the cells seen in the image cones, or abnormally large rods? Why do only some cells appear to be missing from the photoreceptor mosaic? If these cells are non-functioning cones, why do they stay in the retina instead of degenerating?

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Little work has been completed on achromatopsia, partly because of the rarity of the disease. To date there are only four histology studies of achromatopic eyes. Each concludes completely different results regarding the photoreceptor distribution throughout the eye; one study found normal cone densities in the fovea with reduced numbers of cones in the periphery\textsuperscript{24}, while another found no cones in the fovea and reduced numbers elsewhere.\textsuperscript{25} The fact that the causes for achromatopsia are genetically heterogeneous could account for these discrepancies. Rochester plans to image multiple achromats with different genetic mutations to determine if and how genotype affects the retinal phenotype.

The Rochester Adaptive Optics system was used to image a cone-rod dystrophy patient, CA. Cone dystrophy is characterized by cone photoreceptor cell death, resulting in a central blind spot. This also leads to photophobia, where the patient prefers low light levels over a brightly illuminated environment. In the patient imaged at Rochester, the fundus photograph Figure 2.43 shows a slight darkening of the macula. This central region corresponds to the patient’s central blind spot. Adaptive optics images were taken just outside of this blind spot, in a normal appearing area of the fundus. As seen in the image below, there appear to be missing or non-functioning photoreceptors in the image even though the fundus photograph appears normal in this area. Again, questions arise such as, what is happening in these areas to cause photoreceptor death? How do adaptive optics images of the “affected” fundus area compare to the “unaffected” area? How would images of retinal locations further into the periphery appear? This research continues at the University of Rochester. Little work has been completed on achromatopsia, partly because of the rarity of the disease. To date there are only four histology studies of achromatopic eyes. Each concludes completely different results regarding the photoreceptor distribution throughout the eye; one study found normal cone densities in the fovea with reduced numbers of cones in the periphery\textsuperscript{26}, while another found no cones in the fovea and reduced numbers elsewhere.\textsuperscript{27} The fact that the causes for achromatopsia are genetically heterogeneous could account for these discrepancies. Rochester plans to image multiple achromats with different genetic mutations to determine if and how genotype affects the retinal phenotype.

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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.42.png}
\caption{Adaptive Optics image of achromatic eye. Patient: RM, OD, 2.5 degrees temporal retina.}
\end{figure}

\textsuperscript{24} Falls et al. Typical total monochromacy. A histological and psychophysical study. \textit{Arch. Ophthalmol.} 1965; 74(5):610-6
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Figure 2.43: Left: Fundus image of cone-rod dystrophy patient. Central macula is darker than normal. Right: Adaptive optics image of cone-rod dystrophy. Patient: CA, OD, 5 degrees superior retina.

2.2.3.7. Future Plans for Year 6
During Year 6, Rochester plans to continue research to further the understanding of retinal diseases using the current Rochester Adaptive Optics system, as well as an adaptive optics scanning laser ophthalmoscope (AOSLO) being built from funding through a NIH-BRP grant. The CfAO through its MEMS mirror development effort is closely associated with these projects. Year 6 projects at Rochester include:

Imaging the Mosaic of a Stargardt’s Macular Dystrophy Patient over Time. Visual acuity decreases rapidly in these patients; initially patients have 20/20 vision that can decrease to 20/200 within a few years. By initially imaging a patient early in the progression of the disease and repeating the imaging over time, it may be possible to observe the photoreceptor death corresponding to the decrease in visual acuity.

Imaging RPE Cells with Autofluorescence. The retinal pigment epithelial cells in the human retina are responsible for phagocytosis of the outer segments of the photoreceptors. Phagocytosis is a process in which the outer segments are digested and replaced with new outer segments. As a byproduct of this process autofluorescent molecules, specifically lipofuscin, accumulate in the RPE cells. The accumulation of lipofuscin is known to increase with age, therefore the autofluorescent signal increases with age. In addition, unusual amounts of lipofuscin, and thus abnormal autofluorescence, can be seen in numerous retinal diseases including age-related macular degeneration and Stargardt’s macular dystrophy. Understanding this accumulation could provide insight to the etiology of these diseases. During Year 6, Rochester will attempt to image the autofluorescence of the RPE layer on a cellular level with the BRP AOSLO instrument.

Imaging Primate Ganglion Cells Using the Fluorescence Adaptive Optics Scanning Laser Ophthalmoscope. Ganglion cells are transparent cells that lie in front of the photoreceptors as light enters the eye. They pool signals from different photoreceptor types and send the resulting visual signal to the brain. The goal of this project is to label specific ganglion cell types through fluorescent injections in the awake primate brain, then image those cells with the Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO). The AOSLO will be equipped with a laser for activating the fluorescent dye and with filters to image only the emitted fluorescent light. The high resolution of the instrument, combined with the high contrast of the fluorescence, will provide \textit{in vivo} images of transparent cells never achievable before. Since the cells will be imaged in live monkeys, it will be possible to perform psychophysical testing to determine the function of specific ganglion cell types. It will also be possible to damage certain cells and test the resulting visual performance.

Imaging of photoreceptors in retinitis pigmentosa. Retinitis pigmentosa (RP) is a retinal dystrophy characterized by night blindness and reduced visual fields. While retinitis pigmentosa is a relatively rare disease, gene therapies are being made to increase the survival rate of photoreceptors. Currently there are rat and dog models for retinitis pigmentosa. The photoreceptors in the RP animals will be tagged with a green fluorescent protein molecule to assist in photoreceptor cell imaging. The BRP AOSLO instrument will provide the first \textit{in vivo} assessment of the disease model in these animals. In addition the animals have received gene therapy for retinitis pigmentosa. Survival rates of photoreceptors in the treated rats and dogs will be assessed \textit{in vivo} using the BRP AOSLO instrument and compared with photoreceptor counts in untreated diseased animals to determine the effectiveness of the treatment.
3. EDUCATION

3.1.1. 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. In the past, we reported our progress through four major goals, created at the end of Year 1. These past goals have served us well, providing a focus for our efforts as we developed new programs and activities. But we have found that the structure of the original goals does not adequately represent our evaluation and reporting needs: we need to look at the impact of our programs from a range of different perspectives, and at varying levels. Consequently we have developed four major strategies that encompass our original goals, and provide a consistent reporting structure that can be used at a site-, programmatic-, or higher-level view of our efforts. One of the major reasons for this restructuring was the new NSF requirement for diversity plans.

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.

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

- Number of CfAO members involved in CfAO EHR
- Number of CfAO members who 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 underrepresented undergraduates retained in Science, Technology, Engineering, or Mathematics (STEM) fields
  • Number of underrepresented undergraduates advanced into CfAO, and CfAO related, graduate programs
  • Number of underrepresented graduate students participating in CfAO activities (research and education)

3.1.3. Problems Encountered Reaching Education Goals

One of the major challenges faced by CfAO EHR has been the development of projects on the Big Island of Hawaii. Mauna Kea, located on the Big Island, is extremely important to the astronomical community because of the premier observatories located at its summit. But there is increasing concern for the longer term continuity of the observatories because of weak community support and lack of community involvement in the Observatories. The development of CfAO EHR projects on the Big Island to increase community involvement in observatory activities has been challenging, and has taken several years to implement. A major effort was undertaken in the past year to encourage observatories to host local college students for internships. We were disappointed that only two observatories took interns, but feel that with this start we will have more success in 2005. Our new Akamai Observatory Short Course gained a great deal of attention from the observatories and the general public, and will provide a leverage tool for increasing the involvement of observatories next year. Several have already indicated their interest.

3.2.1 The Center's Internal Educational Activities

3.2.1.1 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</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>40</td>
</tr>
</tbody>
</table>

Web link: http://cfao.ucolick.org/EO/PDWorkshop/
Goals:
1) Develop inquiry-based teaching skills in 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 annual CfAO Professional Development Workshop brings together graduate students, postdoctoral researchers, and education partners for an intensive week of activities on teaching and learning science. Participants compare hands-on approaches to teaching, engage in their own personal inquiry experience, and participate on an inquiry design team. The Workshop is held in Hawaii, a focus for US astronomical observatories. Participants 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 while being directly mentored by workshop staff. In 2004 these leadership roles were formalized and returning participants were matched in roles that related to their past experiences and interest in developing new skills. Roles included: inquiry co-facilitator, inquiry shadower, discussion group leader, design team leader, assessment activity leader. 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 can be 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 practice their new teaching skills, and then reflect on their experience with peers. This combination of the workshop and the teaching experience has led to the development of many new inquiry activities and an emerging 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 finding from the survey is available in a report prepared by our external evaluator, Julie Shattuck and Associates, at
A most significant gain reported by participants was the pre/post shift in their confidence in 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, below).

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 determine how they incorporated inquiry into their activities. The following inquiry activities were all designed by teams of participants from the Professional Development Workshops:

- 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 Observatory Short Course)
- Table Top Optics (Stars, Sight and Science)
- Camera Obscura (Akamai Observatory Short Course)
- Lenses and Refraction (Akamai Observatory Short Course)
- Photodiode Activity (Akamai Observatory Short Course)
- Physiology of the Eye (Rochester Saturday Open Lab)
- Color Vision Inquiry (Rochester Saturday Open Lab)

### 3.2.1.2 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>

**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 submit one-page proposals outlining the planned content of a visit to a CfAO site so as to gain experience in a different discipline. For example, astronomers can apply to visit vision science sites and vice versa.

**Outcomes: In Year 5, one Mini-Grant was completed:**
Marcos van Dam, a postdoctoral researcher at LLNL, spent a week at Don Miller’s Lab at Indiana University's School of Optometry. He learned about AO systems for vision science and obtained "hands-on" experience of a working system in order to write a chapter in CfAO's Vision Science AO Manual. Marcos collaborated with the staff there to improve the performance of their AO system by using the knowledge he had acquired while working with Keck Observatory's AO system. A significant improvement to the stability of the Indiana AO system was attained after Marcos isolated a bug in the centroiding code. In addition, Marcos worked with Don Miller’s group to add several new features to the AO system.

- Background subtraction in the wave-front sensing camera.
- Image sharpening to remove static aberrations.
- Reconstructors for varying pupil sizes.
- Modal reconstructors using Zernike polynomials in addition to the existing zonal reconstructor.

![Fig. 3.3 Karen Thorn, Ravi Jonnal, and Marcos Van Dam at Don Miller’s lab, during Marcos' Mini-Grant experience.](image)

**3.2.2. Professional Development Activities**

1. Annual Professional Development Workshop – The workshop (more fully described in Section 2a) builds teaching, collaborative teamwork, communication, and other important skills. It helps build a community among the CfAO’s young researchers.
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, with national and international participation as well as participation from within the CfAO.

4. Center Retreats and Topical 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.

3.2.3 The Center's External Educational Activities

3.2.3.1 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>
<tr>
<td>Intended Audience</td>
<td>Primarily underrepresented high school students</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>15-18 each year</td>
</tr>
</tbody>
</table>

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 from groups under-represented in science and technology to prepare themselves for a STEM degree (2-year or 4-year) at the college level.

Project Description:
The four-week summer immersion experience includes three coordinated courses on vision science, astronomy, and science communication developed by CfAO:
1. Astronomy Today: Observing the Universe
3. 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*, confirming the institutional commitment to this successful program. The CfAO now pays for 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\(^\text{29}\) students, providing them with interdisciplinary, inquiry based experiences and small group projects led by CfAO graduate student advisors. The instructional team includes lead instructors, project advisors, guest instructors, and a high school science teacher. Watsonville High School science teacher Gary Martindale has worked with the CfAO instructional team for three years, assisting with project advising and providing teaching guidance. This year he is teaching the “transferable skills” course, working closely with CfAO to incorporate communication and other skills into the program. 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.

\(^{29}\) Underrepresented minorities are defined here as Hispanic, African American, Native American, Pacific Islander.
The *Stars, Sight and Science* program is one of CfAO’s “teaching labs.” All instructors, and most project advisors have attended 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 using both vision science and astronomy content. In addition, the lead instructors have developed several different mechanisms for assessing students’ learning. In 2004 they will assess students’ understanding of optics (learned through an optics inquiry) by evaluating their ability to apply concepts in a written “knowledge survey” and a transfer task.

**Table 3.1**

**Outcomes of Stars Sight and Science Program**

<table>
<thead>
<tr>
<th>Status of Stars, Sight and Science participants (2001-2003 cohorts)</th>
<th>#</th>
<th>%</th>
<th>In high school *</th>
<th>In college</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>14</td>
<td>32%</td>
<td>7</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Female</td>
<td>30</td>
<td>68%</td>
<td>11</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Underrepresented minority</td>
<td>37</td>
<td>84%</td>
<td>14</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Other ethnicity</td>
<td>7</td>
<td>16%</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Underrepresented group (women or minority)</td>
<td>41</td>
<td>93%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not underrepresented</td>
<td>3</td>
<td>7%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*In high school during the 2003-2004 school year.

**3.2.3.2 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, from underrepresented groups, with an emphasis on community college students</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>14-16 each year</td>
</tr>
</tbody>
</table>

**Web link:** [http://cfao.ucolick.org/EO/internshipsnew/mainland/](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 a 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 personal network. Throughout the internship, communication is an ongoing theme. At the end of the summer, interns give a ten-minute formal oral presentation on their project. Because for many students this is their first experience in presenting at this level, we have implemented a set of activities that provide instruction and resources for the students to enable them to prepare and deliver a 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. Its goal is to establish a sense of community among the students; prepare them for the research environment; orient them to the CfAO; and provide the necessary background for a successful experience in the multi-disciplinary CfAO environment. 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. This short course was developed by CfAO graduate students and has now become a model for three other CfAO short courses. The Mainland Short Course is one of CfAO’s “teaching labs,” providing opportunities for testing new inquiry-based teaching activities.

In Year 5, a new element was developed for recruiting interns: Saturday Open Labs, a one-day activity that assists sites in recruiting students by engaging them in an inquiry-based science activity. In Year 5, our first Saturday Open Lab was held at University of Rochester. Twelve students from a local community college signed up, and nine actually attended. Of these, seven applied to the summer internship program, and one was accepted. Also see: http://cfao.ucolick.org/EO/internshipsnew/satopenlabs/.

Outcomes: Students are tracked over time formally through surveys, and informally through continuing contact with CfAO members. We track the following: major, institution attended, applications/acceptances into graduate school, and entry into the workforce. We also track participation in research and other programs, including scholarships and other awards. Although it is too early to report retention, graduation, or graduate school entry rates, we are very pleased with our interns’ progress (see Table 3.2). From the 2001-2003 cohort, 26 of the 29 students are still on track in a STEM pathway.

One of our biggest challenges in EHR has been the difficulty in recruiting graduate students from underrepresented minority (URM) groups. The internship program has been one of our major efforts to address this problem (a “grow your own” strategy). It appears that it will be a successful strategy. Two URM students have now been accepted into graduate programs, one at UCSB in electrical and computer engineering, and one at UCSC in electrical engineering. In addition, another URM student has been awarded a
post-baccalaureate fellowship to participate in research and prepare for graduate school. This fellowship is a joint award from Keck Observatory and the CfAO.

**Table 3.1. Summary of the status of the interns from the 2001-2003 cohorts**

<table>
<thead>
<tr>
<th></th>
<th>#</th>
<th>%</th>
<th>Enrolled undergrad in STEM</th>
<th>Switch-ed to non-STEM</th>
<th>BA/BS earned</th>
<th>Left college w/o degree</th>
<th>Entered grad school in STEM</th>
<th>Entered STEM workforce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>12</td>
<td>41%</td>
<td>8</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Women</td>
<td>17</td>
<td>59%</td>
<td>9</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Underrepresented minority</td>
<td>19</td>
<td>66%</td>
<td>13</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other ethnicity</td>
<td>10</td>
<td>34%</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Underrepresented group (women or minority)</td>
<td>28</td>
<td>96%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not underrepresented</td>
<td>1</td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Our internships have a strong focus on community college students. Community colleges are the fastest growing major higher-education sector, and serve a high percentage of the country’s minority population. Community college students face a number of barriers for completing four-year college, including the transfer process and adjusting to a new institution after transfer. Table 3.3 shows the progress of our community college students (those who enter our program as community college students).

**Table 3.2. Summary of intern status for those who started program as a community college student**

<table>
<thead>
<tr>
<th></th>
<th>#</th>
<th>%</th>
<th>Enrolled at CC</th>
<th>Left CC W/degree or transfer</th>
<th>Now at 4-yr in STEM</th>
<th>Now at 4-yr in non-STEM</th>
<th>Graduated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Community college</td>
<td>15</td>
<td>52%</td>
<td>5</td>
<td>2</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4-year institution</td>
<td>14</td>
<td>48%</td>
<td>n/a</td>
<td>n/a</td>
<td>6</td>
<td>0</td>
<td>8</td>
</tr>
</tbody>
</table>

### 3.2.3.3 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>

The CfAO Akamai Internship is an outcome of our long-term investment in Hawaii partnerships. The internship brings together stakeholders from the Maui and Big Island
communities, with goals of increasing participation of the Hawaiian community in CfAO-related science and technology, and increasing the capacity of Maui Community College to incorporate adaptive optics-related technology into its academic program offerings. In 2004, the Akamai Program expanded onto the Big Island, with the new Akamai Observatory Short Course (see below) and several new internship positions. In Years 6-8 we will refine our Big Island component, based on results from our Summer 2004 efforts.

3.2.3.4. Akamai Optics Short Course
Akamai Interns are prepared for their research experience through the CfAO Optics Short Course, a 5-day intensive experience modeled after the Mainland Internship Short Course. This course was designed by and is taught by a CfAO postdoctoral researcher, Andy Sheinis (with support from his NSF Postdoctoral Fellowship), and a Maui Community College (MCC) faculty member, Mark Hoffman. The Short Course gives students a general background in optics and the scientific process through a set of inquiry based activities supplemented by lectures. In addition, internship hosts give short talks 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/EO/internshipsnew/shortcourses/mauisc.php.

3.2.3.4.1 Research Experience
The Akamai Interns are placed at high tech industry sites (primarily the federal contractors for the Air Force in Maui) and at astronomical observatories. The following organizations hosted interns in 2003 and/or 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

Figure 3.5 Maui Community College student, Sunny Cabello, works on a photodiode detector during the Akamai Optics Short Course
Akamai interns present their summer research at a student symposium at the Student Session of the AMOS Technical Conference held 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). It fosters collaboration between the technical and educational communities of Maui, and provides students with an opportunity to experience a professional conference. Family and community members are invited to attend the student symposium; we anticipate that this community element will be informative for the local community and will positively impact the public perception of the use of technology on Haleakala. In 2003 the Student Session attracted the attention of the press, resulting in newspaper coverage of the Akamai program (See Section 8.10. Item 13)

3.2.2.4.2 Outcomes:
The first cohort of students participated in the Akamai Internship Program in the summer of 2003. We are tracking the educational and career progress of these students, as shown in Table 3.4. It is too early to determine the career or educational impact on the interns; however, we are impressed that two interns have continued working at their intern site, and two are now at 4-year institutions.

Table 3.4 Status of former interns in Akamai Internship program

<table>
<thead>
<tr>
<th></th>
<th>#</th>
<th>%</th>
<th>Continued work at intern site</th>
<th>Enroll ed at CC in STEM</th>
<th>AA or transfer</th>
<th>At 4-yr enrolled in STEM</th>
<th>Entered STEM workforce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>8</td>
<td>73%</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Women</td>
<td>3</td>
<td>27%</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Underrepresented minority</td>
<td>4</td>
<td>36%</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Other ethnicity</td>
<td>7</td>
<td>64%</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Underrepresented group (women or minority)</td>
<td>6</td>
<td>55%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not underrepresented</td>
<td>5</td>
<td>45%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2.3.5 Akamai Observatory Short Course

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Akamai Observatory Short Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Claire Max</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Hawaii state residents attending college</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>15-20 annually</td>
</tr>
</tbody>
</table>
The Akamai Observatory Short Course (AOSC) is a one-week intensive experience that prepares college students for internships at observatories. It was held for the first time in Year 5. The course is taught collaboratively by the CfAO and personnel from the Big Island observatories. The AOSC gives students background in astronomy, astronomical observatories, and the scientific method through a set of inquiry-based activities supplemented by lectures and a tour of the Observatories on the summit of Mauna Kea. The course includes a unit on the role of astronomy in Hawaiian culture.

The long-term educational goal of this project is to increase the participation of the Hawaiian community in the State of Hawaii’s technical workforce. This is important to the field of astronomy because of the presence of the country’s premier observatories on the summits of Mauna Kea and Haleakala volcanoes in Hawaii. In addition to the educational goal, it is hoped that the project can help secure the future of astronomical research on the summit of Mauna Kea, which has come under criticism by community groups within Hawaii. We will take steps toward building a foundation for improved relations between the astronomical community and the Hawaiian community, so as to increase their acceptance for the presence of observatories on Mauna Kea and to increase the chances for the renewal of the lease for the summit of Mauna Kea when it expires at the end of 2033.

Participants in the AOSC came from two main sources: students who are about to begin summer internships at any of the observatories in Hawaii, and students who are science or technology majors from the University of Hawaii at Hilo, at Hawaii Community College, at Maui Community College, and possibly at the University of Hawaii at Manoa.

**Outcomes:**

A total of 17 students completed the AOSC in Year 5. Their make-up was as follows:

Hawaii state residents = 16
Native Hawaiians = 5
Other underrepresented minorities = 2
Women = 4
Total underrepresented students (women & minorities) = 10
UH Hilo students = 5
Maui Community College students = 2
Honolulu Community College students = 3
UH Manoa students = 1
Hawaiian residents enrolled in mainland universities = 4
Not currently enrolled (recent high school grad) = 1

At the end of the AOSC, 15 of the students completed an evaluation form, and gave very positive feedback on their experience. One of the questions was "Overall, how valuable has the AOSC been to you?"

**Student Responses:**
- not at all valuable = 0
- somewhat valuable = 1 (7%)
- valuable = 5 (33%)
- extremely valuable = 9 (60%)

**Selected quotes from the evaluation form follow:**

"The short course taught me how wonderful it would be to work in an observatory."

"It gave me more motivation in trying to seek different opportunities in the astronomy field. It was exciting to hear the different people from astronomers, EE, optical engineers, to mech. engineers."

"This course was extremely helpful in learning about the observatories in a way that I never knew before. I previously worked at an observatory and didn't know half of what I know now."

"I realized that there are so many opportunities there besides just astronomy and it really seemed to open a lot of doors for my future."

"Gives me a new path and direction. Many new opportunities that did not exist before."

"I realized I would love to work at an observatory. It gives me hope for my future."

We will track the progress of the AOSC participants and report on their educational and career status over the future years.

### 3.2.3.6 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</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Community college students and high school seniors</td>
</tr>
<tr>
<td>Approx # of Attendees</td>
<td>15-20 annually</td>
</tr>
</tbody>
</table>
A new astronomy short course was developed and taught at Hartnell College in June 2004. The course was a collaboration between the CfAO and Hartnell College, a minority serving community college near UCSC. Anne Metevier was the lead instructor and developed this course with support from her NSF Postdoctoral Fellowship, along with the Hartnell planetarium director, Andy Newton. The goal of this short course is to enhance the pathway between Hartnell and UCSC by providing a motivational and preparatory experience that opens new opportunities for students. The course is specifically designed to serve students who are not quite prepared for an internship experience similar to the CfAO Mainland Internship. Anne has attended three CfAO Professional Development Workshops, and has incorporated inquiry-based teaching into the short course in a variety of ways, making use of many of the previously designed CfAO instructional materials (some developed by Anne herself) as well as new activities.

Outcomes:
A total of 19 students enrolled in the Hartnell Astronomy Short Course, which was offered in Year 5 for the first time. At the time of this report, only preliminary information was available on outcomes. However, students provided many positive and insightful comments, such as the quote below:

“Your course provided the information and confirmation I was looking for. I am looking forward to my transfer next fall. You have left me extremely motivated and ready to dive in and swim in the rigorous curriculum offered to science majors. I cannot emphasize enough how your course has affected my way of thinking about my major and my future.”

3.2.3.7 Education 286: Research and practice in teaching and learning science

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Ed 286</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Doris Ash</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Science and engineering graduate students at UCSC</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>15-20 annually</td>
</tr>
</tbody>
</table>

Education 286 is a graduate level course 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) 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 science 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 CfAO 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 is 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.

**Outcomes of 2003 Course:**
Fourteen students formally enrolled in the course, with an additional six auditing it and attending on a regular basis, including three postdoctoral researchers, professors and other CfAO students.

The fourteen enrolled students were from the following departments:
- Astronomy (4 students)
- Engineering (1)
- Chemistry (2)
- Earth Sciences (2)
- Ocean & Biological and Environmental Sciences (2)
- UCLA Astronomy (1)
- University of Hawaii (2) (both were on leave participating in an LLNL trainee program)

**Projects:**
All students completed projects in 2003. As one example, CfAO graduate student Scott Seagroves broadened his experience in inquiry teaching by designing an inquiry activity to explore galaxies. Scott presented this project (“Applying the Institute for Inquiry model in an astronomy context”) in April 2004, and it is available on the CfAO EHR Past Meetings web page, under the date, April 26: [http://cfao.ucolick.org/EO/meetings/past.php](http://cfao.ucolick.org/EO/meetings/past.php).
3.2.4. Integrating Research and Education

All our Center members (PI’s, post-docs, graduate students, research staff) 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 Center’s educational goals. A few illustrative examples of how we have integrated research and education follow:

- To date, 29 undergraduates have worked on CfAO related research (2001-2003 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 CfAO vision-science graduate student Jason Porter (University of Rochester).
- CfAO graduate students and postdocs developed 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, taught by Center PI’s, postdocs, and graduate students.
- CfAO members have developed many new inquiry-based instructional activities in optics, astronomy, vision science, and instrumentation. See the list under the “Professional Development Workshop, above.
- All CfAO retreats, and nearly all CfAO presentations, include an education and human resources component.

3.2.5. Plans for Year Six

3.2.5.1 Annual Professional Development Workshop
This project will continue in the same general format, with an increasing emphasis on formalizing the roles 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. During Year 6, our focus will be on publishing our workshop model and its impact on young scientists.

3.2.5.2 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.

3.2.5.3 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 has begun moving from a CfAO program to a UCSC program, and we will continue to take steps toward institutionalization in the coming year.

3.2.5.4 Mainland Internship Program
We have developed a strong internship program, which will be continued with minor refinements each year. A major focus in the coming years will be to contribute to the knowledge base on the impact of undergraduate research experiences. We will be part of a new study, AScILS (Assessing Science Inquiry and Leadership Skills), which will explore how students gain inquiry and leadership skills during research experiences, and how the development of those skills affects their educational and career progress.
3.2.5.5  Akamai Internship Program
This internship program based in Maui is still being refined. We will be strengthening the elements of the program that prepare students for an industry environment, and developing a more in-depth orientation for our industry mentors. We will also incorporate broader recruitment to expand the applicant pool.

3.2.5.6  Akamai Observatory Short Course
This short course was extremely successful in its first year, and will be continued in the coming years. In addition to refinement of the curriculum, we will focus our effort on involving a broader range of Mauna Kea observatories.

3.2.5.7  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 College, and further developing the academic pathway for Hartnell students to transfer to UCSC in physics and astronomy.

3.2.5.8  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, and we will focus on taking the necessary steps to having the course permanently adopted by the Education Department. We will encourage science departments to follow the example of UCSC’s chemistry department by including this as an elective course counting toward a doctoral degree.
4. KNOWLEDGE TRANSFER

4.1.1 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 5, the CfAO continued to emphasize knowledge transfer by employing strategies articulated in its mission statement:

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

In addition, specific objectives for knowledge transfer include:

1. Increasing national competence in AO within the scientific, medical, and industrial communities.
2. Enhancing the cohesiveness of the AO technical community, particularly with respect to system performance characterization and optimization.

4.1.2 CfAO Performance and management indicators

The indicators that measure the success of CfAO partnership activities in meeting our objectives include:

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

4.1.3 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. In Year 4, we expanded on the concept of an Industrial Advisory Board by launching an Industrial Affiliates Program, whereby companies that join can become stakeholders in the Center’s progress and play a more active role in utilizing its research or suggesting new paths to follow. In Year 5, three companies participated in the Industrial Affiliates Program. In the future, we hope to grow this industrial investment by increasing the number of participating companies and/or increasing the user fees to a level commensurate with the support of a graduate student for one year. The Laboratory for Adaptive Optics at UCSC has the potential to be a focal point for these industrial activities, but more progress needs to be made in soliciting and obtaining industrial participation and investment in this facility and its personnel.
We have carried out a broad range of effective CfAO knowledge transfer activities during Year 5 within six focus areas. These activities are summarized in the following sections, along with future plans for the Center’s knowledge transfer program.

### 4.2.1 Description of Knowledge Transfer Activities

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Industrial Advisory Board, Industrial Affiliates Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Kevin O’Brien</td>
</tr>
<tr>
<td>Participants</td>
<td></td>
</tr>
<tr>
<td>Organization Name</td>
<td>Address</td>
</tr>
<tr>
<td>1 Multiple organizations (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The CfAO Industrial Advisory Board (IAB) was organized in Year 3 in order to improve our industrial relations. The goals of the IAB are to:

1) Enable effective transfer of knowledge developed by CfAO research to the industrial community – increase interaction between industrial and CfAO personnel.

2) Provide industrial perspective and advice to CfAO researchers for planning of $4M annual NSF funded research and development program (the AODP).

3) Move towards the organization of an Industry Affiliates Program to enable more industry-directed research on adaptive optics leveraged from ongoing CfAO research.

An Industrial Affiliates Program was launched in Year 4. In Year 5, three companies were members: Cibavision, Raytheon, and Carl Zeiss Meditec. Discussions are ongoing with many other companies, particularly concerning support for graduate students working in the Laboratory for Adaptive Optics at UCSC.

<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>Participants</td>
<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 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, and many do so. Emphasis is on topics that are of interest to both astronomers and vision scientists. Introductory and Advanced AO are presented in alternate years. Each year approx. 100 participants attend. In 2004, 54 of those attending were graduate students, 19 were post docs, 24 were senior researchers and 19 were speakers.
<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>Workshops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Multiple leaders (see below)</td>
</tr>
</tbody>
</table>

Participants

<table>
<thead>
<tr>
<th>Organization Name</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple organizations (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The CfAO sponsors multiple workshops each year. These range from large formal AO sessions at international meetings to smaller special-topics discussions. Workshops in Year 5 included:

2003, 10/02 — ExAO Workshop:
The goal of the workshop was to discuss requirements and techniques for achieving XAOPI's calibration and static wavefront sensing goals. There were 17 participants.

2003, 10/16-17 — Tomography Workshop.
Harry Barrett, Regents Professor, Professor of Radiology, Professor of Optical Sciences, and Professor of Applied Mathematics at The University of Arizona, was the featured facilitator/lecturer at this two-day interactive problem-solving workshop on AO Tomography, held at UC Santa Cruz. There were 15 attendees.

2003, 11/7-10 — Fall Science and Education Retreat
Held at Tenaya Lodge, just outside of Yosemite National Park in California. 115 graduate students, postdoctoral researchers and other members attended. Topics included AO for astronomy and vision science, education, and industrial sessions. There were 27 members of industry in attendance.

2003, 12/16 — XAOPI Strawman Optical Review Workshop
Held at UC Santa Cruz. There were 26 participants

2004, 04/5-6 — Analysis Modeling and Simulation of Adaptive Optics for Extremely Large Telescopes Workshop
The goal of this workshop was to aid in the development of valid analytic and simulation models for MCAO system behavior, in order to produce a viable point design for an MCAO system on an Extremely Large Telescope. There were 26 participants.

2004, 04/07 — Strategic Planning Meeting
This was an interactive workshop held to discuss the direction of research and funding for Years 6-10 for the Center. Participation was limited to CfAO principal investigators. Thirty-nine PIs attended the day-long session.

2004, 05/10-12 PSF Workshop held in Victoria, Canada.
There were 25 people in attendance at this workshop, including several via a video link.

2004, May 16-21 — CfAO Professional Development Workshop
Title: "Connecting Science Education Practice and Theory." The workshop was held in Maui, HI.
2004, 07-08—Extreme Adaptive Optics Coronagraph “Kick-off” Workshop. There were 25 participants at this working meeting to discuss design plans for our Gemini extreme adaptive optics proposal.

<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</td>
<td></td>
</tr>
<tr>
<td>Organization Name</td>
<td>Address</td>
</tr>
<tr>
<td>1 11 Maui Interns</td>
<td>Maui, Hawaii</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 in Maui. The interns, most of whom were placed in local high-tech industries, received course credit from MCC.

The Center also offers a wide range of short courses through its Education Activities. These have been described in detail in Section 3.2.3.4

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>AO test-bed for vision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>David Williams</td>
</tr>
<tr>
<td>Participants</td>
<td></td>
</tr>
<tr>
<td>1 Multiple organizations (see below)</td>
<td></td>
</tr>
</tbody>
</table>

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. This year the University of Rochester vision AO system has been used by at least four different research groups outside the CfAO. The PIs of these research groups were:

- Jay and Maureen Neitz, Medical College of Wisconsin
- Pablo Artal, University of Murcia
- Phil Kruger, SUNY College of Optometry
- John Flannery, UC Berkeley

<table>
<thead>
<tr>
<th>Knowledge Transfer Activity</th>
<th>AO Manual for vision science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Jason Porter</td>
</tr>
<tr>
<td>Participants</td>
<td></td>
</tr>
<tr>
<td>1 Multiple organizations (see below)</td>
<td></td>
</tr>
</tbody>
</table>

The CfAO continued work on a manual that will contain basic and detailed information on how to design, build, calibrate and implement adaptive optics systems for vision science applications. This manual is targeted towards scientists, researchers, engineers and students who are interested in constructing their own vision science adaptive optics systems. The manual will contain chapters authored by experts in their respective fields and exemplifies the collaborative nature of the Center between vision scientists and astronomers. Chapters are being written and reviewed by editorial and technical reviewers in the vision science and astronomical communities. Wiley Interscience has agreed to publish the manual. The manual is expected to be published in the Summer of 2005 and will serve as one of the long-term “monuments” for the CfAO. Jason Porter (University...
of Rochester) is the lead editor and organizer for this project and Julianna Lin (University of Rochester), Hope Queener (University of Houston), Karen Thorne (Indiana University) and Abdul Awwal (LLNL) are the members of the editorial committee. Several CfAO members in the vision science and astronomical communities are contributing chapters for this book. (A list of the chapters and their contributors may be found on the CfAO web page: http://cfao.ucolick.org/pubs/manual.php.) By Year 6, the only remaining tasks associated with the book will be proofing and indexing.

4.2.2 Other Knowledge Transfer Activities

The CfAO web site (http://cfao.ucolick.org) is an important vehicle for knowledge transfer. Information is available about the CfAO at this web site, including research projects, education and human resources activities, membership, meetings, publications, distributed software, employment opportunities, and the 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 later in this Report.

CfAO members play leadership roles in professional societies concerned with adaptive optics, serve on organizing committees for international conferences on adaptive optics, and present results of CfAO research. In 2004 Scot Olivier, the CfAO Associate Director for Knowledge Transfer, was named as 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 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 and fiber lasers, and involves at least 9 universities, national laboratories and industrial partners.

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 a highly effective means of knowledge transfer since the new collaborative programs include participants both inside and outside the Center.

The work on AO for giant segmented mirror telescopes has involved numerous CfAO researchers as part of the California Extremely Large Telescope (CELT) project and the Thirty Meter Telescope (TMT) project. Claire Max, our Associate Director for Theme 2,
is a member of the national GSMT (Giant Segmented Mirror Telescope) Science Working Group. An outcome of these activities in Year 5 has been 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 has been named as the Interim Project Scientist for TMT. All five US members of the TMT AO Working Group are CfAO researchers (including its Chair, Donald Gavel), as is one of its two Canadian members.

The Laboratory for Adaptive Optics At UCSC, funded by the Moore Foundation starting in Year 4, continues to provide crucial laboratory facilities and expertise for Themes 2 and 3 of the Center.

The University of Rochester and 5 partner institutions entered the second 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. In addition a team led by UC Davis, and including 2 CfAO member institutions, Indiana University and LLNL, began 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.

In connection with the CfAO’s EHR Professional Development Workshop, in Year 5 a Community Networking Session was 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 the educational and industrial communities in Maui. CfAO continued its strong interaction with an LLNL intern program for native Hawaiians (NSFEI – ALU LIKE) with five more interns in Year 5. The interns toured Lick Observatory, learned about AO, and attended the Akamai Observatory Short Course in June of Year 5. 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. See Section 3.2.3 for other short course offerings.

### 4.2.3 Knowledge Transfer Activities - Future Plans

In the future 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, particularly in astronomical AO, to publish their research in a timely fashion. As described above, we are writing a manual on the design, implementation, characterization and optimization of AO for vision applications. This manual will be published by Wiley Interscience, and will represent a major resource for the field and a key component of our strategy to enable widespread use of AO in vision science.

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 6 will include AO for ophthalmic instrumentation, AO for giant segmented mirror telescopes, MEMS, and lasers for laser guide stars. We will establish 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. Our 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 6.

The CfAO seeks to develop a growing number of industrial partnerships. The Center has active partnerships with 11 companies in Aerospace (Lockheed Martin), Ophthalmology (Bausch and Lomb, Wavefront Sciences), Communications (AOptix), MEMS (Lucent Technologies, Boston Micromachines, IrisAO, Intellite), Liquid Crystals (Hamamatsu), Lasers (Lite Cycles) and Detectors (Rockwell).

As we move forward, the CfAO will aggressively pursue new industrial partnership opportunities provided by our growing outreach activities, including our Industrial Advisory Board and our new Industrial Affiliates program.
5. EXTERNAL PARTNERSHIPS

5.1.1 Partnership Objectives

The 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 in its mission statement:
1. Leveraging our efforts through industry partnerships and cross-disciplinary collaborations
2. Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology

In addition, specific objectives for partnerships include:
3. Stimulating further investment by government and industry sources in AO research and development
4. Catalyzing the commercialization of AO technologies, leading to technological advancements relevant to CfAO research objectives and enabling broader use of AO.

5.1.2 Performance and management indicators

The 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.

5.1.3 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. To address this issue, we instituted an Industrial Advisory Board and in Year 4 an Industrial Affiliates program. However the issues remain complex, and we are continuing to seek guidance on best practices in the commercialization of the type of medical imaging instrumentation being developed by the Center.
5.2.1. Description of Partnership Activities

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Vision Science using the Rochester AO test bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>David Williams</td>
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<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>1 Bausch and Lomb, the Medical College of Wisconsin, and the Schnurmacher Institute for Vision Research, State College of Optometry, State University of New York</td>
<td>AO vision test-bed</td>
<td></td>
</tr>
</tbody>
</table>

As part of the key Vision Science Theme goal to make AO broadly accessible to the scientific and medical community, the University of Rochester has established partnerships with Bausch and Lomb, the Medical College of Wisconsin, and the Schnurmacher Institute for Vision Research, State College of Optometry, State University of New York, along with ongoing collaborations with CfAO member institutions: the University of Houston, Indiana University and Lawrence Livermore National Laboratory.

<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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<thead>
<tr>
<th>Name of Organization</th>
<th>List Shared Resources (if any)</th>
<th>Use of Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 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>
<td>Adaptive Optics scanning laser ophthalmoscopes</td>
<td></td>
</tr>
</tbody>
</table>

The University of Rochester is leading an 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: 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 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. In a related development, a U.K. company, Optos, has made plans to incorporate adaptive optics in a wide field scanning laser ophthalmoscope using intellectual property held by the Universities of Rochester and Houston.
**Partnership Activity:** Clinical testing of MEMS AO phoropter  
**Led by:** David Williams

<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>Lawrence Livermore National Laboratory, Sandia National Laboratory, Boston Micromachines Corporation, Wavefront Sciences, Bausch &amp; Lomb</td>
<td>MEMS based Adaptive Optics Phoropter</td>
<td></td>
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</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. This new instrument can be used to measure and correct the high order aberrations in the human eye, thereby enabling 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 AO phoropter 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 this instrument 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 – ~2.5 microns, compared with ~1.5 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, 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

<table>
<thead>
<tr>
<th>Name of Organization</th>
<th>List Shared Resources (if any)</th>
<th>Use of Resources</th>
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<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>
<tr>
<td>CfAO institutions - LLNL and University of Indiana</td>
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</table>

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 first year of this project, we have partnered with Duke University to develop a high-sensitivity OCT system, and we have designed an en face scanning laser imaging system with AO. These two systems will first be tested and optimized separately before being combined. In a related activity, CfAO researchers at the University of Rochester and Indiana University have coauthored a report for Carl Zeiss Meditec on the benefits of combining AO and OCT. This work was arranged through our Industrial Affiliates Program, which Carl Zeiss Meditec has joined.

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Micro-electro-mechanical systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Scot Olivier</td>
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<tr>
<td>Participants</td>
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<tr>
<td>Name of Organization</td>
<td>List Shared Resources (if any)</td>
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<tr>
<td></td>
<td>Use of Resources</td>
</tr>
<tr>
<td>1  A national consortium, organized by the CfAO, to develop MEMS deformable mirror technology for adaptive optics for vision science and astronomy</td>
<td></td>
</tr>
</tbody>
</table>

The CfAO coordinates a national consortium of universities (UC Berkeley, Boston University, UC Davis, Stanford University), national laboratories (LLNL, SNL, AFRL, JPL) and industrial partners (Lucent, Boston Micromachines, Cronos, MEMX, Intellite, Iris AO, AOptix, MicroAssembly Technologies) to develop MEMS deformable mirror technology for adaptive optics suitable for application to vision science and astronomy. In Year 5, Boston Micromachines delivered a 140-actuator mirror with ~2.5 micron stroke, and is working on a version with 3.5 micron stroke. AOptix has delivered a 37-actuator bimorph mirror with a 10-mm clear aperture and ~70 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 a 1000-actuator mirror for testing in the ExAO test bed at the UCSC Laboratory for AO. Lucent is also working on a 1000-actuator mirror concept that is planned to be delivered to UCSC for testing this year.

Building on the CfAO MEMS consortium, LLNL over the period 2001 to 2004 led the successful $12M Phase 1 DARPA Coherent Communications, Imaging and Targeting (CCIT) Program to develop and field-test high-speed MEMS spatial light modulator (SLM) technology with 32x32 pixels. In Year 5, the $13M Phase 2 CCIT Program was awarded to Lucent, a partner in CfAO and in CCIT Phase 1, to develop and commercialize MEMS SLM devices with 64x64 to 256x256 pixels.

Based in part on the CfAO and CCIT work, LLNL has been awarded a $1M, 2-year NSF Adaptive Optics Development Program contract to develop deformable mirrors suitable for giant (30-m) telescopes based on MEMS actuation of nanolaminate optics (a precision-
engineered multilayer material developed at LLNL and elsewhere for a variety of applications including x-ray optics); work is beginning on this activity.

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Lasers</th>
</tr>
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<tbody>
<tr>
<td>Led by</td>
<td>I. Edward Kibblewhite; 2. Deanna Pennington</td>
</tr>
</tbody>
</table>

### 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>1 Lite Cycles, Coherent Technologies, The AFRL at Kirtland Air Force Base, LightWave Electronics.</td>
<td>[ ]</td>
<td>[ ]</td>
</tr>
<tr>
<td>2 European Southern Observatory Hampton University, Iona, IRE Poulus Group, TuiOptics, Fibercore and the IPHT fiber institute in Jena, Germany.</td>
<td>Fiber laser laboratory at LLNL</td>
<td>[ ]</td>
</tr>
</tbody>
</table>

**Solid-State Lasers:** 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 has been successfully completed and the laser has been shipped to Palomar Observatory for deployment. Coherent Technologies Inc. is working on a contract from Gemini to develop another approach for an improved laser head for this general class of laser, and they plan to deliver a system to be deployed on Gemini later this year. AFRL is working with Lightwave Electronics on another laser head variation for this class of laser, and they have successfully tested a 20 W version of the laser on the sky at the Star Fire Optical Range at the AFRL. The NSF has awarded a grant to the Keck Observatory for an operational solid-state laser for the Keck I Telescope, and Keck will solicit industry bids for the contract later this year.

**Fiber Lasers.** LLNL has a project within the CfAO to study fiber lasers, complementary aspects of which have been supported by internal funding at LLNL. An international research collaboration has been established with the European Southern Observatory which has resulted in the provision of equipment and manpower by ESO to LLNL and CfAO. Significant industrial contacts have been established to produce the new custom technology components required for this research, namely Iona, IRE Poulus Group, TuiOptics, Fibercore and the IPHT fiber institute in Jena, Germany. Fiber laser amplifiers with output power over 10 W at 2 infrared 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 also been awarded a grant from the NSF Adaptive Optics Development Program to extend this fiber laser work to a pulse format more suitable for use on giant (30-m class) telescopes that will require multiple laser beacons.

### 5.2.2. Other Partnership Activities

In the area of design of AO systems for giant segmented mirror 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 are 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 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. Therefore, the work on TMT AO design is being coordinated directly with the CfAO Theme on AO for Extremely Large Telescopes.

5.2.3. Partnership Activities - Future Plans

1. Leverage opportunities provided by the Industrial Advisory Board and the new Industrial Affiliates Program to develop new industrial partnerships.
2. Continue to extend our leveraged partnership activities in the area of the development and assessment of prototype clinical ophthalmic instrumentation.
3. Continue to drive the development of MEMS for vision science and astronomical applications through partnerships coordinated within the framework of our national MEMS consortium.
4. Continue to develop a partnership with the Air Force Maui Optical Station that combines technical research and development with education and human resource development.
5. Focus on design concepts for AO systems on giant segmented telescopes in partnership with the TMT project.

The Vision Theme is exploring a number of relationships with companies in an effort to commercialize adaptive optics-related technology.

1. Bausch and Lomb. Rochester will continue to work with Bausch and Lomb on customized contact lenses and testing the MEMS AO Phoropter constructed by LLNL.
2. Carl Zeiss Meditec. Jessica Wolfing, Don Miller, and David Williams have coauthored a report on the benefits of combining adaptive optics and OCT, as a first step toward developing a stronger relationship between Zeiss and CfAO. Zeiss will visit Rochester in Y6 to examine the AO Phoropter which they may wish to commercialize.
3. Ciba Vision. Have expressed an interest in visiting Rochester to examine the AO Phoropter, which they may wish to commercialize.
4. Wavefront Sciences. has expressed an interest in building a second generation AO Phoropter.
5. Reichert. This company has the largest market share worldwide of the phoropter business. They have expressed an interest in visiting Rochester to examine the AO Phoropter, which they may wish to commercialize.
6. Optos. They plan to incorporate adaptive optics in a wide field scanning laser ophthalmoscope using IP held by Rochester and Houston.
6. DIVERSITY

6.1.1. 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

6.1.2. Performance and management indicators

For Management and Performance assessment purposes the CfAO has the following categories for its Diversity Program:
- Tools
- Practices
- Partnerships & Linkages
- People.

The performance and management indicators are identified below for each of these categories

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

100
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
- Number of underrepresented graduate students participating in CfAO activities (research and education)

6.1.3. Challenges in making progress

The challenge faced by the CfAO can be seen throughout the U.S. STEM graduate programs: women, underrepresented minorities, and U.S. citizens in general, are not pursuing doctoral degrees at the numbers that would be appropriate to their representation in the U.S. college age population. For some of our sites, the challenge is in finding students from underrepresented groups, for others it is in finding U.S. students from any ethnic group or gender.

6.2.1. Activities and impact

While diversity initiatives and activities are integrated throughout the CfAO EHR theme, 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. This is a reflection of the low entry and persistence rates of underrepresented groups amongst undergraduates in CfAO related fields. Although we continue our recruitment efforts at the graduate level, our early experience 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:

6.2.1.1 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 2001-2003, 29 students have been accepted into the program (66% underrepresented minority [URM]; 59% female; 96% URM or female). Of those 29, 26 are still on an STEM education/career path. Five of these students will begin graduate school in 2004 (3 women; 2 URM).

In June 2004 an additional 16 students were accepted into the program. Of the 16, 11 are women, 11 are URM; 15 are either women or URM.

6.2.1.2 Akamai Internship Program:
Summer research experiences for college students who are Hawaii residents. The goal of the program is to retain and advance students in technical and scientific fields relevant to the state of Hawaii. In 2003, 11 students were accepted into the program (36% URM; 27% female; 55% URM or female; 100% Hawaii residents; 100% community college
students). Two students have now transferred to a 4-year institution, one has entered the STEM workforce.

6.2.1.3 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.

6.2.1.4 Hartnell Astronomy Short Course:
An intensive one-week course to motivate students to pursue astronomy/physics, and apply for 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).

6.2.1.5 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 two graduate students: 1 at UCLA affiliated with A. Ghez (U.S. citizen, white, female); 1 at UCSC in electrical engineering (U.S. citizen, Hispanic, male).

6.2.1.6 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 will spend the 2004-2005 academic year preparing for graduate school and participating in research under the supervision of Jerry Nelson (UCSC) and Sean Adkins (Keck).

6.2.1.7 Participation in minority serving organizations:
The CfAO has participated in the SACNAS (Society for Advancement of Chicanos and Native Americans in Science) 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 now are funding three of our Hispanic interns, and we directly recruited two of our interns this year from SACNAS.

6.2.1.8 Stars, Sight and Science:
Four-week residential science program for high school students. The goal is to motivate high school students to pursue science in college. 44 students have been through the program (2001-2003), 30 female; 37 URM; 41 female or URM. Fourteen have entered college, or will be this fall.

6.2.1.9 Saturday Open Labs:
Saturday Open Labs are one day events designed for targeted recruiting at CfAO sites. At the University of Rochester the event focuses on encouraging students from a local community college to apply to the CfAO internship program. In 2004, the outcome of this event was seven applications, with two students accepted into the program.
6.3. Plans for Year 6

All of the above diversity activities will be continued in Year 6, with refinements as determined from our program evaluations this summer (many are in progress or were recently completed at the time of this report).

Graduate student recruitment: As described early in this section, graduate student recruitment has been an ongoing challenge for us. At some sites, the difficulty has been in finding qualified applicants from underrepresented groups. At others, such as Indiana University, the challenge is finding U.S. students from any gender or ethnicity.

CfAO Mainland interns are advancing through their undergraduate education, and many are now becoming prospective graduate students. In the coming years, we will be assisting these students in the graduate application process and encouraging them to apply to CfAO sites. This year we implemented a new activity within our Mainland Internship Program, weekly meetings that expose students to our major sites and opportunities at those sites. Each week one of our senior CfAO members gives an informal talk on their research interests, the students in their lab, where students go after working with them (e.g. positions they now hold), and graduate admission processes. We have had a very positive response from the 2004 interns, and will expand this activity in the coming years.

At Indiana University we will implement a new Saturday Open Lab that will focus on recruiting graduate applications from qualified U.S. students, with an emphasis on students from underrepresented groups. We will seek 5-6 U.S. students at the junior level, majoring in physics or engineering, to attend a one-day event at Indiana University. We will draw from a student-pool consisting of Indiana University, nearby institutions, and past CfAO interns, selecting prospective students who are qualified. Don Miller’s lab will host a day of activities and presentations designed to get students interested in submitting graduate applications to IU School of Optometry in their senior year.

We have also identified several other areas for improvement in the coming years. The Akamai program should have better representation of women, both on the Big Island and Maui. This September, we are scheduling a strategic planning meeting with our Hawaii partners to address this concern in particular and to plan a long-term trajectory for the partnership.
7. MANAGEMENT

7.1 Infrastructure Aspects

7.1.1 Center Organization
There has been an adjustment to the management of the Center for Adaptive Optics (CfAO) at the University of California, Santa Cruz. Professor Jerry Nelson has been the Director of the Center since its inception, and plans to continue in that role but share some of his responsibilities with Professor Claire Max, who will assume the role of Deputy Director. Dr. Chris Le Maistre will continue in his position as Managing Director. See Organization Chart – Appendix B.
Professor Nelson has recently been appointed the Project Scientist for the 30-meter telescope study to be jointly undertaken by the California Institute of Technology and the University of California with an initial $35 million of Moore Foundation funding. These studies are closely aligned with the Adaptive Optics applications in the Extremely Large Telescope theme of the CfAO and Professor Nelson’s involvement enhances the research contributions he is making in this theme. However, his new responsibilities necessitate considerable travel, and absences from campus. Consequently, to ensure the Center continues operating efficiently, he has invited Professor Claire Max to assume the role of Deputy Director, and to act as Director in his absence with final decision-making responsibility. Professors Nelson and Max have worked closely together within the Center and will maintain this close working relationship in the future.
Professor Max has a distinguished career both as a scientist and administrator at the Lawrence Livermore National Laboratory and is the Associate Director for Theme 2 – Extremely Large Telescopes within the CfAO. She will continue to be the Associate Director of the Center’s Theme 2.
The Center’s External Advisory Board and its Program Advisory Committee have both been informed of the adjustment in the management structure and have endorsed and lauded the appointment of Claire Max as Deputy Director of the CfAO and acting Director in Jerry Nelson’s absence.

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. The Center management realized that The Center Director was over extended from having taken on additional time consuming duties. To compensate for this maintain operation efficiency the CfAO has appointed a Deputy Director with full decision making authority in the Director’s absence.

7.2. Center Integration – Processes implemented
No changes from previous report.
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>
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<tbody>
<tr>
<td>1 Burney Le Bouef</td>
<td>Associate Vice Chancellor, Research</td>
</tr>
<tr>
<td>2 David Kliger</td>
<td>Dean Natural Sciences</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>
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</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:

The Program Advisory Committee

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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</thead>
<tbody>
<tr>
<td>1 Dr. James Belectic</td>
<td>W. M. Keck Observatory, HI</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. Steven Vogt</td>
<td>University of California, Santa Cruz, CA</td>
</tr>
<tr>
<td>5 Dr. Malcolm Northcott</td>
<td>AOPTIX Technologies, Campbell, CA</td>
</tr>
<tr>
<td>6 Dr. Fiona Goodchild</td>
<td>University of California, Santa Barbara, CA</td>
</tr>
<tr>
<td>7 Dr. Joyce Justus</td>
<td>University of California, Santa Cruz, CA</td>
</tr>
</tbody>
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The External Advisory Board

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dr. Christopher Dainty (Chair)</td>
<td>Imperial College, London, UK</td>
</tr>
<tr>
<td>2 Dr. Pablo Artal</td>
<td>Universidad de Murcia, Spain</td>
</tr>
<tr>
<td>3 Dr. Robert Byer</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. Robert Kirschner</td>
<td>Harvard-Smithsonian, CfA, Cambridge, MA</td>
</tr>
<tr>
<td>6 Dr. Matthew Mountain</td>
<td>Gemini Observatory, Hilo, HI</td>
</tr>
<tr>
<td>7 Dr. Allan Wirth</td>
<td>Adaptive Optics Associates, Cambridge MA</td>
</tr>
<tr>
<td>8 Dr. Harold MacAlister</td>
<td>Georgia State University, Atlanta, GA</td>
</tr>
<tr>
<td>9 Dr. Sidney Wolff</td>
<td>National Optical Astronomy Observatories, Tucson, AZ</td>
</tr>
<tr>
<td>10 Dr. Robert Fugate</td>
<td>Air Force Research Labs, Albuquerque, NM</td>
</tr>
<tr>
<td>12 Dr. David R. Burgess</td>
<td>Boston College, Boston, MA</td>
</tr>
</tbody>
</table>

7.4. Changes to the Center’s strategic plan

The plan remains unaltered. The nature and structure of the three research themes has attracted additional funds to supplement their thematic programs.
8. CENTER-WIDE OUTPUTS AND ISSUES

8.1. Center Publications

8.1.1. Year 5 Peer Reviewed Publications


8.1.2. Year 5 Peer Reviewed Publications: Submitted Only:

3. Year 5 Book Chapters


4. Year 5 Publications: non-peer Reviewed


8.2. Conferences


3. de Pater, I., “LOFAR and Low-frequency Radio Emissions from Jupiter”. EGS-AGU, Nice, 6-12 April 2003 (EAE03-A-03135)


8.3. Other Dissemination Activities

8.3.1. Talks and Lectures:
1. Bierden: Lecture at Boston University graduate level MEMS course on adaptive optics and applications
2. Bierden: Gave talk to senior engineering students at Boston University on application of adaptive optics.
9. Ghez: 04/03/04 Public/General Talks: American Association of Physics Teachers, Southern California Group, Los Angeles, CA
10. Ghez: 05/18/04 Public/General Talks: Sackler Prize Ceremony, Tel Aviv, Israel
16. Ghez: 06/25/04 Lecture: Massive Stars in Interacting Binaries, Quebec, Canada
17. Muller: Blake Lin, “Selectively Addressed MEMS Deformable Mirror Arrays for Adaptive Optics,” presentation to industrial members of the Berkeley Sensor & Actuator Center (BSAC) at the BSAC Industrial Advisory Board Meeting, 9 March, 2004, Univ. of California, Berkeley. A write up with copies of the visuals presented incorporated into a technical digest.

18. Sivaramakrishnan: Lecture on Image-Plane Coronagraphy, and Soummer accepted an invitation to lecture on Phase Mask Coronagraphy at the 2004 Michelson Summer School on High Dynamic Range Coronagraphy to be held at Caltech.

8.3.2. Colloquia:
1. Ghez: 11/18/03 Colloquia at Harvard, Theory Group
2. Ghez: 11/20/03 Colloquia at Massachusetts Institute of Technology, Department of Physics
3. Ghez: 01/16/04 Colloquia at Yale University, Miller-Breit Memorial Lecture, Department of Physics
4. Ghez: 01/26/04 Colloquia at NASA Astrobiology Institute, Director's Seminar
5. Ghez: 01/28/04 Colloquia at University of California Santa Barbara, Astrophysics Seminar
6. Ghez: 02/16/04 Colloquia at University of Chicago, Department of Astronomy
7. Ghez: 02/17/04 Colloquia at Northwestern University, Astrophysics Seminar
8. Ghez: 04/01/04 Colloquia at California Institute of Technology, Department of Physics
9. Ghez: 05/03/04 Colloquia at vCornell University, Salpeter Lecture, Department of Physics
10. Ghez: 05/06/04 Colloquia at Cornell University, Department of Astronomy
11. Larkin: During Year 5, James has given 2 invited colloquia at MIT and the Hertzberg Institute for Astronomy on CATS and the NIRC2 galaxy program.

8.3.3. Workshops and Courses:
2. Ghez: 11/13/03 Lecture: “Formation & Evolution of Stars Near the Galactic Center,” Radcliffe Institute Workshop
3. Larkin: In the fall of 2003 (and also in past falls of 1999, 2000, 2001, and 2002), James taught a laboratory course at UCLA for undergraduate astronomy students. As part of this course, we installed a simple AO system (tip-tilt only) on a 24" telescope and the students ran open and closed loop on several bright objects. Approximately 85 students have used the system during the five years.
4. Sivaramakrishnan: and Soummer attended the NASA-ESA invitational High Contrast Coronagraphic Workshop in Leiden, contributing chapters to the ESA-sponsored report on coronagraphy produced by the workshop.
5. Sivaramakrishnan: Makidon will attend the Michelson summer school on coronagraphy (expenses covered by the Michelson Program).
8.3.4. Miscellaenous Activities:
1. De Pater: UC Berkeley astronomers create movie showing hydrocarbon haze that Huygens probe will encounter in Titan's atmosphere 4/15/04 - File # 16575 http://astron.berkeley.edu/~madamkov/titan
3. Ellerbroek: A new AO simulation code (CIBOLA) has been developed for general use and is available at the CfAO website.
4. Larkin: Matthew Barczys is part of a major effort to improve the UCLA planetarium and public telescopes. This has included incorporating CfAO science into public presentations.
5. Le Mignant: 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/
7. Pennington: Formation of a Cooperative Research and Development Agreement with CTI is in progress.

8.4. Awards and other

<table>
<thead>
<tr>
<th>Recipient</th>
<th>Reason for Award</th>
<th>Award Name and Sponsor</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>Andrea Ghez</td>
<td>Merit Recognition</td>
<td>Member National Academy of Sciences</td>
<td>2004</td>
</tr>
<tr>
<td>2</td>
<td>Merit Recognition</td>
<td>Member American Academy of Arts and Sciences</td>
<td>2004</td>
</tr>
<tr>
<td>3</td>
<td>Excellence in Teaching, Research and Science</td>
<td>Gold Shield Faculty Prize (UCLA Award)</td>
<td>2004</td>
</tr>
<tr>
<td>4</td>
<td>Dedication to science, originality and excellence</td>
<td>Sackler Award Tel Aviv University</td>
<td>2004</td>
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<tr>
<td>5</td>
<td>Excellence in Research</td>
<td>Faculty Research Lecturer Award UCLA</td>
<td>2003</td>
</tr>
<tr>
<td>6</td>
<td>Don Gavel, Brian Bauman, Scot Olivier, Kevin OBrien, Paul Bierden</td>
<td>MEMS-based Adaptive Optics Phoropter One of the 100 most technologically significant new products in year 2003</td>
<td>2003</td>
</tr>
<tr>
<td>7</td>
<td>James Larkin</td>
<td>Merit Recognition</td>
<td>2000/2003</td>
</tr>
<tr>
<td>Recipient</td>
<td>Reason for Award</td>
<td>Award Name and Sponsor</td>
<td>Date</td>
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<tr>
<td>Marshall Perrin</td>
<td>Graduate Student Merit Award</td>
<td>Michelson Graduate Fellowship, NASA</td>
<td>2003/2006</td>
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<tr>
<td>Rémi Soummer</td>
<td>Graduate Student Merit Award</td>
<td>Michelson Graduate Fellowship, NASA</td>
<td>2003/2006</td>
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<td>David Williams, Heidi Hofer</td>
<td>The best article in Optics and Photonics News</td>
<td>Archie Mahan Prize awarded by the Optical Society of America</td>
<td>October, 2004</td>
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<tr>
<td>Stacey Choi, Joe Carroll</td>
<td>Recognition for Conference Presentation</td>
<td>Hot Topics: Association for Research in Vision and Ophthalmology</td>
<td>2004</td>
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<tr>
<td>Ravi S. Jonnal (Co-authors: Junle Qu, Karen Thorn, Donald T. Miller)</td>
<td>En-face coherence gating of the retina with adaptive optics</td>
<td>2003 ARVO Travel Grant for best oral presentation at ARVO Conference</td>
<td>2003</td>
</tr>
<tr>
<td>Joy Martin</td>
<td>The best paper on one of the following topics: Geometrical Optics; Physical Optics; Ophthalmic Optics; Optics of the Eye</td>
<td>Julius F. Neumueller Award in Optics, American Academy of Optometry</td>
<td>12/2003</td>
</tr>
<tr>
<td>Blanca Marinez (CfAO Intern)</td>
<td>Undergraduate student Merit Award</td>
<td>An award for one of the top presentations at the SACNAS conference</td>
<td>2003</td>
</tr>
<tr>
<td>Abhiram Vilipuru</td>
<td>Research studying glaucoma in a monkey model</td>
<td>Fight for Sight Postdoctoral Research Fellowship</td>
<td>2004/05</td>
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<tr>
<td>Lynne Raschke, Michael Helmbrecht</td>
<td>Graduate Student Merit Award</td>
<td>President's Dissertation-Year Fellowship UCSC</td>
<td>2004/05</td>
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<tr>
<td>Michael Helmbrecht</td>
<td>Technology Recognition Award</td>
<td>Retinitis Pigmentosa International Vision Awards: Retinal Technology Vision Award</td>
<td>2004</td>
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</table>
### 8.5 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>Yrs. to Degree</th>
<th>Placement</th>
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<tbody>
<tr>
<td>Mike Flanagan, University Montana</td>
<td>Ph.D</td>
<td></td>
<td>TREX, Hawaii</td>
</tr>
<tr>
<td>Eric Steinbring, Ph.D UC Santa Cruz</td>
<td>Postdoc</td>
<td></td>
<td>Herzberg Institute of Astrophysics, Canada</td>
</tr>
<tr>
<td>William Donnelly Univ. of Houston</td>
<td>MS</td>
<td>3</td>
<td>Univ. of Houston - Ph.D. Student.</td>
</tr>
<tr>
<td>Tiffany Glassman UC Los Angeles</td>
<td>Ph.D</td>
<td>6</td>
<td>SPITZER Science Center</td>
</tr>
<tr>
<td>Suvi Gezari UCLA</td>
<td>MS</td>
<td>3 Years</td>
<td>Columbia UniversityPh.D. Student,</td>
</tr>
<tr>
<td>Gabriella Canalizo Postdoc LLNL</td>
<td>Postdoc</td>
<td></td>
<td>UC Riverside - Faculty,</td>
</tr>
<tr>
<td>Henry Roe UC Berkeley</td>
<td>Ph.D</td>
<td>5</td>
<td>Caltech (Postdoc)</td>
</tr>
<tr>
<td>James P. Lloyd UC Berkeley</td>
<td>Ph.D</td>
<td>5</td>
<td>Caltech (Postdoc)</td>
</tr>
<tr>
<td>James P. Lloyd, Ph.D Caltech (Post doc)</td>
<td>Postdoc</td>
<td></td>
<td>Faculty, Cornell University</td>
</tr>
<tr>
<td>Heidi Hofer University of Rochester</td>
<td>Ph.D</td>
<td>6</td>
<td>Oxford University</td>
</tr>
<tr>
<td>Nathan Doble, Ph.D University of Rochester</td>
<td>Postdoc</td>
<td></td>
<td>Iris, AO</td>
</tr>
<tr>
<td>Aris Pallikaris University of Rochester</td>
<td>MS</td>
<td>2</td>
<td>University of Crete</td>
</tr>
<tr>
<td>Junle Qu, Ph.D University of Indiana</td>
<td>Postdoc</td>
<td></td>
<td>Institute of Optoelectronic, Shenzhen University, China</td>
</tr>
<tr>
<td>Karen E. Thorn, Ph.D University of Indiana</td>
<td>Posttdoc</td>
<td></td>
<td>IBM, New Zealand</td>
</tr>
<tr>
<td>Ramesh Sundaram University of Houston</td>
<td>MS, electro engineering</td>
<td>2</td>
<td>A.P. Software Inc. Boston, MA</td>
</tr>
<tr>
<td>Ricky Sepulveda MD University of Houston</td>
<td>Incomplete</td>
<td></td>
<td>Ophthalmology Residency in Cleveland, Ohio</td>
</tr>
<tr>
<td>Daniel Good, Grad UC Berkekely</td>
<td>Incomplete</td>
<td></td>
<td>Left to join a start-up company</td>
</tr>
<tr>
<td>Anne Metevier UC Santa Cruz</td>
<td>Ph.D</td>
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<td>Astronomy, UC Santa Cruz (postdoc)</td>
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</table>
8.6. 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>Determination of ocular refraction from wavefront aberration data &amp; design of optimum customized correction. Williams, D.R., Guirao, A.</td>
<td>U.S. Patent #6,511,180</td>
<td>10/00</td>
<td>January 28, 2003</td>
</tr>
<tr>
<td>Method and Apparatus for Using Adaptive Optics in a Scanning Laser Ophthalmoscope. A. Roorda</td>
<td>60/316,173</td>
<td>8/30/01</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>
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<tr>
<td>Method and Apparatus for the Correction of Optical Signal Wave Front Distortion using Fluid Pressure Adaptive Optics. B. Sadoulet</td>
<td>020321D1</td>
<td>3/28/02</td>
<td></td>
</tr>
<tr>
<td>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>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>
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<tr>
<td>Repeatable Mount for MEMS Mirror System. Stephen Eisenbies, Steven Haney</td>
<td></td>
<td>October 4, 2002</td>
<td></td>
</tr>
<tr>
<td>Actuator Apparatus and Method for Improved Deflection Characteristics, M. Helmbrecht</td>
<td>10/705,213</td>
<td>November 2003</td>
<td></td>
</tr>
<tr>
<td>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>
</tbody>
</table>

**Name of Start-Up Company**

| 1 | Iris AO, Berkeley, CA | MEMS digital-mirror arrays for adaptive optics |
8.7. Outputs of Knowledge Transfer Activities made during the reporting period not listed above.

Nil.
8.8 Summary listing of all of the Center’s research, education, knowledge transfer and other institutional

<table>
<thead>
<tr>
<th>Organization Name</th>
<th>Organization Type*</th>
<th>Address</th>
<th>Contact Name</th>
<th>Type of Partner**</th>
<th>&gt;160 hours</th>
</tr>
</thead>
<tbody>
<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>N</td>
</tr>
<tr>
<td>Maui Community College</td>
<td>Academic</td>
<td>310 Kaahumanu Kahului, 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>
<td>Y</td>
</tr>
<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>
<td>N</td>
</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>
</tr>
<tr>
<td>Akimeka - Maui</td>
<td>Company</td>
<td>535 Lipoa Parkway, Kihei, Maui, HI 96753</td>
<td>Andrew Vliet</td>
<td>Education</td>
<td>N</td>
</tr>
<tr>
<td>Trex - Maui</td>
<td>Company</td>
<td>MRTC, Suite 222, 590 Lipoa Parkway, Kihei, Maui, HI 96753</td>
<td>Allen Hunter</td>
<td>Education</td>
<td>N</td>
</tr>
<tr>
<td>Maui High Performance Computing Center (MHPCC)</td>
<td>Government</td>
<td>550 Lipoa Parkway, Kihei, Maui, HI 96753</td>
<td>Gene Bal</td>
<td>Education</td>
<td>N</td>
</tr>
<tr>
<td>Institute for Astronomy</td>
<td>Academic</td>
<td>PO Box 0209, Kula, HI 96790</td>
<td>Mike Maberry</td>
<td>Education</td>
<td>N</td>
</tr>
<tr>
<td>Textron - Maui</td>
<td>Company</td>
<td>535 Lipoa Parkway, Suite 149, Kihei, HI 96753</td>
<td>Michael Reilly</td>
<td>Education</td>
<td>N</td>
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<tr>
<td>Smithsonian Submillimeter Array (SMA)</td>
<td>Observatory</td>
<td>645 North A’ohoku Place, Hilo, Hawaii 96720</td>
<td>Billie Chitwood</td>
<td>Education</td>
<td>N</td>
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<td>Organization Name</td>
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<td>Type of Partner**</td>
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<tr>
<td>13 Exploratorium Science Center</td>
<td>3601 Lyon Street San Francisco, CA 94123</td>
<td>Barry Kluger-Bell</td>
<td>Education</td>
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<tr>
<td>14 Keck Observatory</td>
<td>Observatory 65-1120 Mamalahoa Hwy Kamuela, HI 96743</td>
<td>Fred Chaffe</td>
<td>Education/Research</td>
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<tr>
<td>15 Gemini Observatory</td>
<td>Observatory 670 N. A'ohoku Place Hilo, Hawaii, 96720</td>
<td>Peter Michaud</td>
<td>Education/Research</td>
<td>N</td>
<td></td>
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<tr>
<td>16 Hispanic Associate for Colleges and Universities (HACU)</td>
<td>Not Profit 8415 Datapoint Drive, Suite 400 San Antonio, TX 78229</td>
<td>Tony Leiva</td>
<td>Education/Diversity</td>
<td>N</td>
<td></td>
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<tr>
<td>17 University of Hawaii – Hilo</td>
<td>Academic 200 W. Kawili St. Hilo, HI 96720-4091</td>
<td>Richard Crowe</td>
<td>Education/Diversity</td>
<td>N</td>
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<tr>
<td>18 Watsonville High School</td>
<td>Academic 250 E. Beach St. Watsonville, CA 95076</td>
<td>Gary Martindale</td>
<td>Education/Diversity</td>
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</tr>
<tr>
<td>19 Center for Informal Learning and Schools (CILS)</td>
<td>Academic 3601 Lyon Street San Francisco, CA 94123</td>
<td>Sally Duensing</td>
<td>Education</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>20 ALU LIKE</td>
<td>Non profit 458 Keawe Street Honolulu, HI 96813</td>
<td>Doug Knight</td>
<td>Education/Diversity</td>
<td>N</td>
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<tr>
<td>21 Educational Partnership Center</td>
<td>Academic U.C. Santa Cruz 3004 Mission Street, Suite 220 Santa Cruz, CA 95060</td>
<td>Carrol Moran</td>
<td>Education/Diversity</td>
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<tr>
<td>22 Carl Zeiss-Meditec</td>
<td>Company 5160 Hacienda Dve. Dublin, CA 94568</td>
<td>Barry Kavoussi</td>
<td>Research</td>
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<td>23 Northrop Grumman - Maui</td>
<td>Corporation P.O. Box 398 Makawao, HI 96768</td>
<td>Albert Esquibel</td>
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<tr>
<td>24 Lucent Technologies</td>
<td>Company Bell Labs. Murray Hill N.J</td>
<td>David Bishop</td>
<td>R &amp; D</td>
<td>Y</td>
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<tr>
<td>25 Intellite</td>
<td>Company 1717 Louisiana, Suite 202 NE Albuquerque NM 87110</td>
<td>Dennis Mansell</td>
<td>R &amp; D</td>
<td>N</td>
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<tr>
<td>26 Ciba Vision Corporation</td>
<td>Vision Company 11460 Johns Creek Parkway Duluth Georgia 30097</td>
<td></td>
<td>R &amp; D</td>
<td>N</td>
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<tr>
<td>27 Coherent</td>
<td>Laser 135 South Taylor</td>
<td>Tim Carrig</td>
<td>R &amp; D</td>
<td>Y</td>
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<tr>
<td>Organization Name</td>
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<td>Contact Name</td>
<td>Type of Partner**</td>
<td>&gt;160 hours</td>
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<tr>
<td>Technologies Inc.</td>
<td>Company</td>
<td>Ave, Louisville, CO 80027</td>
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<tr>
<td>Wavefront Sciences</td>
<td>Company</td>
<td>14810 Central Ave, Albuquerque NM 87123</td>
<td>Tim Turner</td>
<td>R &amp; D</td>
<td>Y</td>
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<tr>
<td>Bausch &amp; Lomb</td>
<td>Company</td>
<td>One Bausch &amp; Lomb Place Rochester NY 14603</td>
<td>Peter Cox</td>
<td>R &amp; D</td>
<td>Y</td>
</tr>
<tr>
<td>MEMX</td>
<td>Company</td>
<td>1368 Bordeaux Drive Sunnyvale CA 94089</td>
<td>Jim Koonmen</td>
<td>R &amp; D</td>
<td>Y</td>
</tr>
<tr>
<td>Lockheed ATC</td>
<td>Company</td>
<td>Palo Alto CA</td>
<td>John Breakwell</td>
<td>R &amp; D</td>
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</tr>
</tbody>
</table>

8.9 Summary Table

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>the number of participating institutions (all academic institutions that participate in activities at the Center)</td>
<td>11</td>
</tr>
<tr>
<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>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>The total leveraged support (sum of funding for the Center from all sources other than NSF-STC)</td>
<td>$4,035,987</td>
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<tr>
<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>198</td>
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124
8.10 Media Publicity the Center Received.


2. Miller: Newspaper publicity: The Indianapolis Star “IU working to bring inner eye into focus” (front page of Section B), The Cincinnati Enquirer “Astronomy tool adapted for eye exams”, The Daily Telegraph “Galactic technology may fight blindness” (Sydney, Australia), The Sydney Morning Herald “What’s good for the stars is good for damaged eyes” (Sydney, Australia), Associated Press Newswires “IU scientists adapting astronomy tool for eye exams”


4. Miller: Indiana University media publicity “Major technical advance in astronomy improves diagnosis -- relations of eye diseases”, IU Home Pages “Stars in the eyes”, Indiana Alumni Magazine “New optics bring retina into focus”, IU Update video for half-time “Optometry uses astronomy technology” -- basketball show on ESPN

5. Christou: Intensive search in aftermath of shuttle explosion helps solve riddles - Great Falls Tribune, Friday, December 26, 2003 By ROBERT LEE HOTZ, The Los Angeles Times (Excerpt) “Lacking comprehensive data from Columbia’s onboard electronics, NASA accident investigators in February and early March had to rely on engineering intuition and technical analysis -- informed guesswork. Investigators were intrigued by a blurred image of the shuttle taken by two off-duty Air Force officers at the Starfire Optical Range in Albuquerque. A volunteer -- Julian Christou, a research specialist at the Center for Adaptive Optics at University of California at Santa Cruz -- sharpened the picture through days of intensive computerized image enhancement, using techniques developed to clarify images of distant galaxies. Even with his best efforts, the image of Columbia remained a smudge, but it revealed signs of an unusual disturbance around the leading edge of the left wing. It could have been caused by a crack, a dent or a tear in its skin. Engineers at NASA’s Langley Research Center looked at the data and wondered how that could match the only clues they had to work with: Columbia’s last seconds of telemetry signals transmitted to Mission Control in Houston. The signals showed four failing sensors in the wheel well and abnormal temperature readings from two sensors along the back of the left fuselage. What damage near the front of the craft would cause a flow pattern that would affect temperatures at the rear?”

6. Williams: B&L’s eye system wins OK Company aims to double its share of lasik vision surgeries. (By Michael Wentzel October 11, 2003, Democrat and Chronicle Rochester, NY) With approval from the Food and Drug Administration for its custom laser eye surgery system, Bausch & Lomb Inc. is aiming at doubling its share of procedures performed in the United States and boosting revenue from the surgeries. B&L’s Zyoptix system allows a surgeon to create a precise map of a cornea that measures the unique imperfections in each patient’s eye. The system is based on “adaptive optics” technology developed by David Williams, a University of Rochester professor, and his colleagues.

7. Williams/Yoon Expanded vision By Michael Wentzel January 4, 2004 (Democrat
Excerpts: “In his laboratory on the University of Rochester’s River Campus, Geon-Young Yoon is developing a new kind of contact lens — a customized lens that could correct for the many unique imperfections in a person’s eyes and significantly improve vision. Teams of Bausch & Lomb and Eye Institute researchers meet monthly and, in some instances, weekly. These ties between B&L and the university already have paid off. B&L’s customized laser vision correction platform — called the Technolas 217z Zyoptix system — is based on “adaptive optics” technology developed by David Williams, a UR professor, and his colleagues. Zyoptix allows a surgeon to create a precise map of a cornea that measures the unique imperfections in each patient’s eye.”

“Yoon is recruiting adult patients who have vision problems after a corneal transplant or who have a condition known as keratoconus, an abnormal cone-shaped cornea. He will use adaptive optics technology to measure the imperfections in each patient’s eye. A laser will sculpt a soft contact lens designed to counter the patient’s unique optical aberrations. The National Eye Institute has awarded $750,000 to Yoon for the lens project, which will include about 30 adults. B&L will help make the lenses, which could be forerunners of custom-designed contact lenses for other vision problems.”

8. TMT: Foundation awards $17.5 million for Thirty-Meter Telescope plans; CALIFORNIA INSTITUTE OF TECHNOLOGY NEWS RELEASE
Posted: October 20, 2003
The dream of a giant optical telescope to improve our understanding of the universe and its origin has moved a step closer to reality today. The Gordon and Betty Moore Foundation awarded $17.5 million to fund a detailed design study of the Thirty-Meter Telescope (TMT). This new grant allows the California Institute of Technology and its partner, the University of California, to proceed with formulating detailed construction plans for the telescope.

BERKELEY – Astronomers at the University of California, Berkeley, have discovered the nearest and youngest star with a visible disk of dust that may be a nursery for planets. "Circumstellar disks are signposts for planet formation, and this is the nearest and youngest star where we directly observe light reflected from the dust produced by extrasolar comets and asteroids - i.e., the objects that could possibly form planets by accretion," said Paul Kalas, assistant research astronomer at UC Berkeley and lead author of a paper reporting the discovery. The research was supported by the NASA Origins Program and the National Science Foundation's Center for Adaptive Optics.
10. **Astrophysicists use laser guide star adaptive optics**  
DOE/Lawrence Livermore National Laboratory  27 Feb. 2004

For the first time, scientists from UC Berkeley and Lawrence Livermore, in conjunction with astrophysicists from the California Institute of Technology, UC Santa Cruz, the National Science Foundation’s Center for Adaptive Optics and UC’s Lick Observatory, have observed that distant larger stars formed in flattened accretion disks just like the sun. Using the laser guide star adaptive optics system created by LLNL scientists, the team was able to determine that some of the relatively young yet massive Herbig Ae/Be stars contain biconical nebulae, polarized jets and circumstellar disks. Less massive stars including the sun are believed to be formed in a swirling spherical cloud that collapses into a disk.

The astronomers observed a strongly polarized, biconical nebula 10 arcseconds in diameter around the star LkHa 198 and a polarized jet-like feature in LkHa 198-IR. The star LkHa 233 featured a narrow, unpolarized dark lane similar to an optically thick circumstellar disk. The research appears in the Feb. 27 edition of the journal Science.

11. **Williams, Carroll Colour blindness cell loss clue:**  
BBC News 2004/06/04 23:00:48 GMT

Scientists have found that some colour blind people are missing as many as one third of the normal number of specialised light-detecting cells. However, apart from colour blindness, the general quality of their sight appears unaffected. The researchers hope their work will enable earlier detection of eyesight disorders. The study, by the University of Rochester, is published in Proceedings of the National Academy of Sciences. The Rochester team used a technique called adaptive optics to study the retina of the eye in much closer detail than has previously been possible. It was originally developed to help astronomers see more clearly through the Earth's atmosphere.

Lead researcher Dr Joseph Carroll said: "Not only are we excited to show how this method can reveal us living cells in a way never before possible, but it's revealed a mystery with profound implications. If a third of the light-receiving cells in your eye are absent and you don't even notice it, it means that when a patient complains to a doctor about waning light sensitivity, then the damage must already be very serious."


12  **Education: WHS grad returns two years later to encourage others**  
By Katherine Morris of THE REGISTER-PAJARONIAN Mar 7 2004

When Blanca Marinez was a Watsonville High School senior sitting in Gary Martindale's chemistry class a few years ago, she never could have imagined the things she'd be able to achieve after graduation. She never knew that by age 19 she'd be in her second year at Cabrillo College working toward a degree in ophthalmology. Nor that she'd work as an intern for the Center for Adaptive Optics in Houston, where she'd win a major award for an innovative eye research project she'd create during her time there. Today, she's sharing the secrets of her success with other young students in hopes that they'll "take some initiative" and "get involved in their education" by seeking out academic camps and internships that are available to them.

"Sometimes people around here, in our community, don't feel very capable," Marinez said. "A lot of people put boundaries on themselves and their lives, and
many people don't have anyone to look up to. That was my experience a lot of the time in high school, but I don't want other students to feel that way. That's why I'm doing this."

As she stood in the front of the classroom - dressed much like the students she was speaking to in blue jeans and large silver hoop earrings - she presented a slide show that she created entitled "The Cuhautli (eagle) in you: Getting involved in your education." The articulate teen covered all the bases from attending special academic summer camps to applying for internships and college.

She also pushed for students interested in the sciences to check out the COSMOS (California State Summer School Program for Mathematics and Science) program at the University of California, Santa Cruz. The four-week residential summer school, which Marinez attended during the summer after she graduated, in 2002, is largely what jumpstarted her academic career.

"If I'd never done COSMOS, I never would have done any of this," she told the class. From the camp, she went on to have an internship with a local ophthalmologist and began attending Cabrillo College, where she's been taking classes to fulfill the pre-med requirements. Last summer, she interned with the Center for Adaptive Optics in Houston and attended the SACNAS (Society for Advancement for Chicanos and Native Americans in Science) convention in New Mexico.

"At the conference, I was able to present the research work I'd been doing on ways for mapping out the human eye with video," Marinez said as she showed a slide of her testing on the human eye. "There were students presenting projects from all over the country, from all sorts of colleges and universities, but I was the only one from Watsonville. It was cool to be able to represent our area."

In the end, Marinez was one of 12 people out of hundreds who received an award for her presentation at SACNAS.

Students were silent and attentive throughout her presentation, mesmerized by Marinez's stories and accomplishments. "Internships are really important because they allow you to go out and work in an environment to find out if you really like being there or not," Marinez said. "It also opens up options to you that you didn't have before, gives you good references for getting into school or getting future jobs and gives you experience. It also introduces you to people with the same goals and interests as you. Sometimes your friends just aren't into what you're into, and this helps you meet people who are."

Now, the COSMOS program and the CFAO, where Marinez interned, have hired her to go around to local schools and encourage students, particularly underrepresented minority populations, to check out internships and programs.

Several students seemed visibly touched by what they'd heard and seen during Marinez's presentation. "Her talk was really good; I liked the whole thing," Watsonville High senior Karina Aguilera said. "When she was talking about the human eye, I learned so much. And I'm interested in that kind of research so it helped to hear her today. You know, there are a lot of people that have a bad conception about Watsonville High - that there are a bunch of Mexicans that don't have plans for high achievements," Aguilera added. "She gave a lot of us encouragement and hope. She seems really smart."
In a basement science lab on the University of Hawaii at Hilo campus, 17 students cluster around two slide projectors at the front of a darkened classroom-turned-laboratory. As members of the inaugural class of the Akamai Observatory Short Course, they are presenting their discoveries and conclusions from the "Inquiry on Color and Light."

The hands-on experiment is one of several topics studied, and concludes a week of 10-hour days spent studying electronics, optics and astrophysics, as well as mechanical and software engineering.

Their teachers are all career researchers, technicians and scientists from the observatories on Mauna Kea, the University of Hawaii's Institute for Astronomy, and graduate students associated with the National Science Foundation-funded Center for Adaptive Optics.

The windowless room is a scientist's dream and a claustrophobe's nightmare, perfect for this experiment: exploring the mysteries of light.

In groups of two or three, students crowd the room and move among their various experimental stations. There are slide projectors, overhead projectors and several rectangular boxes that spill rays of white light onto the table top. A buzz of discovery laced with questions fills the air; rainbows and circles and squares of projected color splash the walls.

The equipment is standard issue for a university's audio-visual supply room. Nothing like the oscilloscopes, spectrometers and multi-meters they'd used with the scientists and technicians of Mauna Kea. But even basic equipment can demonstrate "additive and subtractive" color mixing, putting students in charge of the discovery process.

The students are, in the words of Isaac Newton, "standing on the shoulders of giants who preceded them in discovery."

Funded by the Center for Adaptive Optics (CfAO) and co-sponsored by the W. M. Keck Observatory, the Akamai Observatory Short Course will become an annual outreach program in both Hilo and Waimea.

W. M. Keck Observatory astronomer David Le Mignant and colleague Sarah Anderson worked with the CfAO team of Lisa Hunter, Malika Moutawakkel and Gale Kihoi to coordinate the course, provided free to the students. Astronomy graduate students Patrik Jonsson and Michael McElwain, and professor Claire Max, all from the Center for Adaptive Optics.
Optics, were the principal instructors. Other teachers included staff from the Canada-France-Hawaii, Gemini, Keck and Submillimeter Array observatories who donated their time and expertise. The group spent two days in Waimea and two days in Hilo, with the high point -- literally -- happening Wednesday on the summit of Mauna Kea. The students toured four facilities, stayed for sunset, and enjoyed the rise of a very full moon.
ATTACHMENTS

Appendix A: Biographical Information of New Faculty (No new faculty)

Appendix B: Organizational Chart (following pages)

Appendix C: External Advisory Committees (following pages)
Appendix B: Center Organizational Chart
Appendix C: Minutes of Advisory Committee Meetings

1 Report of the External Advisory Board - May 2004

1.1 Executive Summary

The External Advisory Board of the Center for Adaptive Optics met in Santa Cruz on February 12th 2004 to review the progress and performance of the Center and its activities. We are delighted that funding from NSF has been confirmed for years 6-10, and in view of this situation the EAB felt its meeting should focus on the research strategy and plans for the future.

The Center has developed significantly since the EAB last met in 2002. The management has become increasingly effective and there is a strong focus and sense of purpose in each of the four themes. There has been a very impressive leverage of the $20M NSF funds to approximately $60M from all sources. The CfAO building has been open for 18 months and the new AO laboratory at UC St Cruz is currently under construction.

Claire Max has been appointed Deputy Director, a move we the EAB strongly supports: in view of the extensive commitments of the Director, Jerry Nelson, we suggest that the title "co-director" might be more appropriate.

The Education Theme continues to be very successful and is a model for other NSF Centers. There is a strong emphasis on diversity issues at each site and the education director, Lisa Hunter, has an excellent record of motivating Center research staff to participate in the education program. The EAB encourages continued measurement of the success (or otherwise) of the various activities and supports the tracking of the career paths of the students involved in the Education Theme.

Theme 2, AO for Extremely Large Telescopes, has found its niche in the US and World activity in the subject. There are well-defined goals related to multi-conjugate AO for 30m telescopes, hardware components and in astronomy with laser guide stars. This is a very strong program.

The smaller Theme 3 topic, eXtreme AO, is focused to the point where there is little flexibility in the project, should funding not come through for the XAOPI instrument. Consideration might be given to merging Themes 2 and 3 or to allowing Theme 3 to have a more "enabling" role.

Theme 4, Vision Science, continues its World-leading research. This has been an outstanding activity which seems to get better all the time. A very impressive aspect is the way that different groups around the country have collaborated so fruitfully, clearly demonstrating the benefit of working in "Center mode".

The knowledge transfer and industrial affiliates program are developing well. We strongly encourage the Center to build up their industry connections and look forward to hearing of progress in this area at our next meeting.

Finally we recommend that the next meeting of the EAB be held co-located with a Center retreat so that members of the EAB can interact with a wide range of Center participants.

Pablo Artal (University of Murcia, Spain)
David Burgess (Boston College)
Bob Byer (Stanford University)
Chris Dainty (National University of Ireland, Galway and Imperial College, London) (Chair)
Allan Wirth (by telephone) (Adaptive Optics Associates, Inc)
Sidney Wolff (NOAO)
1.2 External Advisory Board 2004 Report
1.2.1 Introduction
The fourth meeting of the External Advisory Board (EAB) was held on 12th February 2004 in Santa Cruz, almost halfway through Year 5 of the Program. Funding for Years 6 to 10 has been confirmed by NSF, so a major function of the EAB Meeting was to review and advise upon the future research program.

Presentations were given by the Director, Jerry Nelson, and the four Theme Leaders, with an additional presentation by Scot Olivier on Knowledge Transfer and Industry Participation. The EAB had a short Executive Session and then briefed the UCSC Vice President, Burney Le Bouef, on their preliminary report.

1.2.2 Mission
The mission statement states that the purpose of the Center is “to advance and disseminate the technology of adaptive optics in service to science, health care, industry and education”, with the goal “to lead the revolution in AO, by developing and demonstrating the technology, creating major improvements in AO systems, and catalyzing the advances nationwide with the next decade”.

The Center is accomplishing its mission statement. It is acting like a Center and has identified major issues and major problems. CfAO has found a focus and this has enabled CfAO to coordinate and plan activities.

1.2.3 Management Issues
The Management deserve credit for several activities over the past two years and we focus on three of these as follows:

1. The development of roadmaps for Themes 2 and 3. There is a clear set of goals for each program, an appropriate definition of the role of CfAO in the context of other work both in the US and internationally, and clarification of what can be accomplished with CfAO funding and where outside resources will be required. One of the useful features of these roadmaps is that they show the pace that must be maintained during the final five years of operation of the CfAO in order to achieve the major goals of the program. As in any research program, the roadmaps must be viewed as guidelines and not straitjackets; the program must remain flexible enough to take advantage of opportunities as they occur, but the overall achievements that can be expected during the final 5 years of operation of CfAO are now clear.

2. The leveraging of CfAO resources to obtain additional funding. CfAO staff have used the center very effectively to develop collaborations that have succeeded in obtaining substantial additional external funding. For example, CfAO staff were key to enabling four of the six partnerships that were selected for support through the highly competitive Adaptive Optics Development Program, which is funded by NSF and administered by the National Optical Astronomy Observatory (NOAO). Funds for an adaptive optics laboratory at UCSC were obtained from the Moore Foundation and there has been very significant additional funding from NIH and the National Eye Institute for the vision science theme.
3. **Realizing the advantages of operating as a true center.** During the presentations, it was clear that the participants in CfAO are accomplishing projects that lie well beyond the capability of a single institution and that the collaborations between vision scientists and astronomers have produced significant new results. Examples include: 1) the joint approaches to developing MEMS; 2) the application of deconvolution techniques used in astronomical imaging to the interpretation of observations of the structure of the eye; 3) the development and distribution of community software for modeling AO systems.

### 1.2.4 Thematic Issues

#### 1.2.4.1 Theme 1: Education and Human Resources

Over the past three years, the EHR program of CfAO has emerged into a national leadership position in integrating an educational priority into a first rate science and technology effort. During this time, the program has focused its efforts in appropriate ways to become more efficient and to have a more direct impact in all Themes of the center. These changes and greater integration with other themes has led to cultural and organizational changes in the Center and have led to acceptance of EHR into the Center and as a valuable component.

Since Lisa Hunter assumed the position of Associate Director, EHR, there has been increasing focus on a more limited number of initiatives. This decision has been borne out as a sound one. Particularly important was the decreased efforts with K-12 programs. This decision was appropriate at the time and remains appropriate to allow for focus on the major thrusts of the Theme. The continued focus on the college level, transition into college and graduate school entry are paying off and are models for other Centers. One aspect of the next five years, which must remain a high priority, is to develop specific metrics for assessing success of the programs. Tracking students in the various programs is only one way of documenting the effects of the programs. The EHR Program is strongly encouraged to publish reports in peer-reviewed journals in order to document for other centers and similar initiatives successful strategies for educational efforts. In order to succeed in assessment strategies, it does seem logical and entirely appropriate to continue to engage the services of an external evaluator and pursue an increasing focus on publishable research on the impacts of CfAO programs. Partnership with a quality evaluator/researcher may pay big dividends in preparing publications.

The success of the EHR program rests in the reorganization of the initiative into four units: Tools and Ideas; Practices; Organizations and Community; and People. This organizational structure is appropriate and also serves as a useful set of concepts making transmission of the programmatic efforts easier to a broad audience, including the bench scientists in the CfAO. In addition, the organization is appropriate for developing the needed metrics in preparation for publications. Particular accolades go to the program for the partnership with the native Hawaiian-serving Community College and the four-year Hawaiian College. This partnership serves as a model program for others and is an excellent match for the overall theme of CfAO. Early success of the initiative with the Native schools suggests that continued successes will follow. These efforts in Hawaii fully justify and require increased financial resources. It is the understanding of this member of the EAB that an increase in resources for the EHR program are committed by the NSF and it is entirely appropriate to use this increase to support the efforts in Hawaii.

In addition, the program has developed an excellent summer institute for graduate students within CfAO whose activities are judged to be outstanding and having a lasting
impact on the future of these graduate students. The continuing outreach activities whose aim is to increase diversity in the field of adaptive optics are appropriate and should be continued. These partnerships are showing real evidence of success and are to be applauded. Of course, only when the efforts result in increased diversity in the graduate students in CfAO will true success be achieved.

One aspect of the EHR plan over the next few years will be the development of NSF-required Diversity Plans for each of the participating sites. The strategies for developing individual plans appear entirely appropriate and the preliminary plan developed for Rochester is a model. It should be noted that not all sites need develop specific plans for each of the four units. Each site should be encouraged to develop a plan appropriate for its size, its focus and its particular opportunities.

In sum, the EHR initiatives have gained considerable focus and successes over the past few years. This increased focus and organization will continue to serve as a model for other NSF centers and places EHR efforts on equal standing with all other themes in the CfAO.

1.2.4.2 Themes 2 and 3: Adaptive Optics for Extremely Large Telescopes and Extreme AO

One of the major priorities for ground-based astronomy is developing a next generation of large telescopes with diameters of 30 m or more. Diffraction-limited imaging beyond 1 micron is essential for achieving many of the scientific goals identified for these telescopes, which are likely to cost several hundred million to a billion dollars. Building adaptive optics systems for these telescopes is much more challenging than deploying AO systems for 10-m telescopes.

Funding from the Moore Foundation (~$35M) has recently become available to UC and Caltech to pursue the design of a 30-m segmented-mirror telescope (TMT), and additional funds to support design are being expended by NOAO and Canada. Five different AO systems are being discussed for the TMT. The three for which planning is most advanced would provide: 1) diffraction-limited imaging at 1-2 microns over 1-2 arc minute fields to study the assembly of galaxies; 2) mid-IR diffraction-limited imaging to study the environments around young stars where planets form; and 3) very high contrast AO to image planets around other stars.

Successful development of these AO instruments will require advances in both system performance modeling and major technical advances in large format fast, low noise detectors, laser guide stars, large format deformable mirrors with ~5000 actuators, and high speed signal processors.

Themes 2 and 3 are designed to contribute to these developments. We think it is appropriate for CfAO funds, in Theme 2, to be focused on non-telescope specific analysis and modeling and technical developments that will be applicable to all large telescope projects. Simulation and analysis codes have already been developed and made available to the community through the CfAO web site, and further enhancements are in progress. Partnerships have been established to co-fund the development of the necessary technology, including lasers, custom CCDs for wave front sensors, and nano-laminate DM technology.

All of these projects are consistent with the roadmap for AO development in the US. This roadmap was put together by the community with leadership for the planning effort, and advocacy to the NSF for funding, being provided by the CfAO and NOAO. The CfAO has also conducted a number of workshops to engage the community in the development program and to disseminate the results of the work to date.
In order to stimulate community interest in the kinds of science that can be done with AO, CfAO has organized a consortium (Keck, Gemini, Subaru) that will undertake near-IR AO imaging of high redshift galaxies in selected fields that are being studied intensively at a variety of wavelengths with the Hubble Space Telescope, the Spitzer IR Telescope, and other facilities. These data will be archived and made publicly available. This is an innovative experiment that will be very valuable to the extragalactic research community, and the committee looks forward to seeing the scientific results.

In short, the CfAO program in AO for large telescopes (Theme 2) is an essential component of, and is playing a leadership role in, the US drive toward the development of the next generation of ground-based telescopes.

Yellow Laser Program: The CfAO should take a leadership role and help to define the characteristics of the yellow laser transmitter that meets the requirements of the majority of the user communities. This step would assist with the commercial development of a laser system that could be widely applied to AO in astronomy that requires the use of a laser guide star. Ed Kibblewhite’s funding is not high enough to extend his laser research to the next level. His program to generate 5W of yellow has made good progress and is a success. What can the Center do in the area of lasers for guide stars? Define laser specifications and operation features such that the laser system serves most of the users. This will facilitate the development of the laser technology in the commercial marketplace.

1.2.4.3 Theme 3: Extreme Adaptive Optics

Theme 3 has as its primary goal the construction of an Extreme Adaptive Optics (ExAO) system that would enable high contrast imaging at 8- to 10-m telescopes in order to image giant planets in Jupiter-like orbits around nearby stars. This goal is very different from that of the other themes in that it proposes to build a specific piece of hardware, and actual construction requires that several million dollars in outside funding be identified. Since our last meeting, a strawman design and a budget for the instrument have been developed. Detailed modeling and simulations of performance have been completed. High contrast imaging has been demonstrated in a laboratory testbed at UCSC. This initiative is important both as a scientific end in itself and in terms of demonstrating some of the technologies, including deformable mirrors with a large number of actuators, that will be deployed at the proposed 30-m telescope. The first image of an extra-solar planet will obviously be front page news. Some investment in conceptual design is clearly warranted since it is only on the basis of a plausible design that external funding is likely to be obtained, and the concepts developed are likely to be valuable to other groups interested in this kind of science.

That said, however, we think that this project, like Theme 2, should use CfAO funds primarily to explore technologies with broad applicability. Laboratory demonstration that the proposed techniques will achieve the required performance will benefit AO projects outside CfAO. We also endorse the parallel pursuit of high contrast imaging with existing systems, which is ongoing, because publication of scientific results should stimulate broader community interest in, and support of, the level of investment required to realize this breakthrough capability. However, the CfAO should define more clearly when its investment in the specific ExAO instrument that is being proposed will stop and when further progress on the instrument itself will occur only if external funding is identified.
There is a case for merging Themes 2 and 3 into a single program that focuses on techniques and technologies with broad applicability.

1.2.4.4 Theme 4: Compact Vision Science Instrumentation
Theme 4 continues as a model of what the CfAO can accomplish. The vision scientists have benefited from the fact that AO for ophthalmic applications is a new field without such large and entrenched groups as populate the astronomical landscape. David Williams has managed to bring many of the foremost centers of ophthalmic AO research into the theme with spectacular results.

The number of projects and experiments already performed and those proposed in this theme are probably among the most remarkable in the center as a whole. The center was able to put together most of the AO ophthalmic community in the US. In addition, for the first time, it is also apparent that there is some interaction between astronomical and vision researches within the center. A nice example is the use of deconvolution algorithms in high-resolution retinal imaging.

Members of the center have been very successful in attracting a significant amount of additional funding, in particular for equipment-oriented large projects to build AO ophthalmoscopes and AO-OCT systems. During the last years, in this Theme, in addition to instrumental development, some very interesting scientific results have been also obtained and some exciting new experiments are being already proposed.

The situation with MEMS mirrors for vision science is not completely clarified. As it is widely recognized, the future success of this area would require accessible corrector devices with special characteristics for ocular applications and the failure of IrisAO to deliver the promised technology has been a setback. We also suggest the center to try expand its international exposure, especially in this theme.

1.2.5. Other Issues

Affiliates Program
The EAB supports the strengthening of the Industrial Affiliates program. The benefits are for students and for the long term support of the CfAO following the termination of NSF Center funding after the second five year period. Students should be involved in the Affiliates meetings as the program is of great benefit to the students. The CfAO should consider hiring person for Industrial Affiliates program to encourage its evolution. Over time Kevin O’Brien should ramp up his time from 20% to higher level as the program grows.

The role of the EAB
The EAB suggests to the Directors of the CfAO that they look at the EAB and see if it has right kind of expertise to advise the Center on the current and the projected programs.

The EAB should be invited to attend the CfAO Retreat. The EAB meeting could take place on one day attached to the retreat.

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2. The Program Advisory Committee

The Program Advisory Committee met for a full day on May 27, 2004 with members of the CfAO executive committee. This report summarizes the PAC conclusions. Present were:

PAC: Mark Colavita, Stanley Klein (chair), Malcolm Northcott, Steve Vogt. The chair had phone discussions with Fiona Goodchild following the meeting to discuss Theme 1 comments.
CfAO: Jerry Nelson, Chris Le Maistre, Andrea Ghez (via videoconferencing), Lisa Hunter, Claire Max, Scot Olivier, David Williams

At the beginning of the meeting the PAC chair passed out last year's PAC report with a number of the items marked as being worth revisiting. The next section includes several of those items. We include them here for the record, as items that were not discussed by PAC2004, but that maybe are worth remembering.

2.1 Items from the 2003 PAC Report.

2.1.1 Theme 1.
The PAC sees great potential for broadening the impact of the programs by informing others about the availability of course materials and educational opportunities. Several suggestions for broadening were made.

2.1.2 Theme 2.
As part of the "data dissemination" goal of adaptive optics development, the idea of archiving AO data from the Keck OSIRIS instrument seems highly desirable, and NASA/Keck should be encouraged to do this. It might also be desirable if this data could be "National Virtual Observatory" compatible.

2.1.3 Theme 3.
Following up on the questions on additional funding that were also raised by the site committee, the PAC recommends in Year 5 aggressively pursing this additional funding that is required to make ExAO a reality. Besides solicited funding opportunities like the recent NASA TPF call, NASA and other agencies may be open to unsolicited proposals. To that end, discussions with NASA and other agencies would be prudent, as would the production of a significant white paper than can be used for these discussions.

2.1.4 Theme 4.
At the PAC meeting we suggested the possibility of purchasing the intellectual property rights for the flip bonding method to assist Helmbrecht's mirror bonding problem. It might also be wise to develop a clearer view of exactly what the deliverable legacy of CfAO will be for AO on ELT's, and to begin to focus more on achieving that legacy. Is it to be a single-beam CW LGS for an 8-10m class telescope, or a more complex multi-beam pulsed system for MCAO. Is there a need for more diversity in proposals over the next 4 years to achieve that legacy? Should the Director consider issuing a call for "seed grant" proposals, funded by the Director's reserve?

End of extracts from 2003 report

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2.2 2004 Report General Remarks:

The PAC agreed with the CfAO’s Proposal Review Committee on essentially all of their decisions involving allocation of funds to all proposals, including especially their decisions regarding funding cuts to 9 borderline proposals. There was clearly less competition this year for funds, and the funding decisions were less difficult across the board.

The board congratulates Claire Max on her deputy director role, to augment center management given Nelson's increased TMT responsibilities.

The PAC is very impressed with the overall progress made by the CfAO in Year 5. Two areas of major concern identified by the NSF site visit team in 2004, namely the need for large infusions of funding into both Theme 2 Extremely Large Telescopes and Theme 3 – Extreme Adaptive Optics (ExAO), have to a large extent been addressed.

In Theme 2, CfAO researchers have been proactive leaders within the astronomy community, promoting the need for funding to initiate studies for all aspects of the “thirty meter telescope” (TMT) design. The recent funding grants by the AODP and also by the Moore Foundation to Caltech and the University of California are a direct result of these efforts. CfAO researchers are actively participating in all these programs and supplementing the CfAO research effort.

In Theme 3, CfAO is one of two teams currently engaged in a design study for Extreme Adaptive Optics coronograph for the Gemini Observatory. Gemini Observatory expects to fund the building of the coronograph in 2005.

The PAC proceeded with discussions on specific issues within the CfAO’s program, which are covered in the remainder of this report. At next year's PAC meeting we would appreciate hearing how our recommendations were handled.

2.2.1 Theme 1 - Education

In past years, and this year in particular, the PAC has not had adequate expertise in the area of Theme 1. The CfAO director should appoint a new member to the PAC who has expertise in this area and who would attend the PAC meeting.

The focus of our considerations and recommendations are concerned with preparations for the ending of the ten years Center support.

*Overview:* We are impressed by how much the education activities at the Center are being integrated into courses and programs that are now supported by UC Santa Cruz. For example, the high school program is now supported in large part by the campus and the new graduate courses on science education are well subscribed. This progress makes it likely that these initiatives will be sustained indefinitely and will therefore be a legacy of the center. The other major contribution will be a cultural change for the graduate students who had participated in inquiry learning and education. Their options for
teaching and learning have been expanded and we expect that many of them will continue to use inquiry techniques.

**Future funding:** Regarding the idea of looking for more funding, Lisa Hunter is happy to have been granted PI status and has identified NSF education programs that would appear to offer support for educational initiatives that are consistent with the Center's vision. We hope that during this next year one or more grants are submitted.

**Disseminating knowledge:** Over the past few years a good deal of expertise has been developed using inquiry based learning as applied to adaptive optics. The PAC is concerned that AO is extremely specialized, and it may be good to broaden the audience for whom the inquiry based methods are being developed. Stan Klein should meet with Lisa and those persons developing inquiry modules to see whether they may be applicable to teaching optics at member institutions. Rochester, Indiana, Houston and Berkeley have active programs in teaching optics. The latter three with Schools of Optometry may be especially interested in new teaching methods.

**Hawaii:** The political environment for astronomy is really sad right now. Any educational activity that could be there is good. For next year it would be nice to increase Hawaii (main island) activities, and less on Maui. One possibility is to encourage a proposal for next year to fund a person like Lisa for Hawaii, to get involved collaboratively in education with Subaru, CFHT, UKIRT, etc., in addition to the present involvements with Keck and Gemini.

### 2.2.2 Theme 2 – AO on ELT’s

Things appear to be moving along well now as regards laser development with AFRL and Gemini. The committee notes the recent community activity in lasers for AO, including the successful sky testing of the AFRL/LightWave laser at Starfire, as well as the ongoing development by CTI for Gemini North.

**The Sum Frequency Laser:** The PAC did not hear much talk about the Sum Frequency laser effort, a project we came down hard on last year and are watching closely. It appears that the laser did not meet the hard benchmark of 8h @ 5W of continuous operation that we set last year as a condition for further funding to allow tests at Palomar. It is not enough to simply switch the laser on for a short while and measure power. Unless the laser is run for many hours continuously, as in a real observatory setting, the operational test is not valid because there is not time for components to heat up and thereby affect laser stability. *(The laser maintained a power level above 2.5 watts for 3 days continuous operation, the PI and Palomar staff believe that 5 watt continuous operation is achievable CleM)*

In spite of missing this important benchmark, the laser has been shipped to Palomar and will undergo testing there later this year. No funding is being provided for Year 6, but unspent Year 5 funding will be used to support some of the testing at Palomar. The PAC concludes that this laser project at CfAO is in the final stages of termination and will not be pursued by CfAO (beyond perhaps some limited testing at Palomar through the end of Year 5). However, the PAC strongly advises that no new funding be provided unless the 8h @ 5W benchmark has been met. Furthermore, as this laser appears to be not amenable to ever producing the type of pulsed format that is optimal for
AO on ELT’s, the PAC believes that no further funding be provided. On termination of the project, a detailed final report of Laser performance is recommended.

**Fiber Laser:** The PAC is also still hopeful that the CW fiber laser will emerge as a viable contender, though we had expected to see more progress from last year. This laser is still a factor of 10 below the target power of 5 W, but is expected to achieve 5W within a few months. Converting the fiber laser to a suitable pulsed format for ELT’s is also crucial, and should proceed in parallel with increasing the power output. The PAC was also happy to hear that CTI is developing a Cooperative Research and Development Agreement (CRADA) with LLNL to commercialize the laser in pulsed format. Any additional funding that can be leveraged by CfAO in collaboration with AODP and CRADA funds to help push this laser technology forward is a good thing.

**Pulsed formats:** The whole issue of pulse formats is complicated. It may be that even the tested AFRL laser (not CfAO funded) is not useful for ELTs, but may work for existing telescopes. The theme 2 charts shown at the PAC meeting touch on these issues, but don’t make clear the priorities. Is the thinking in the center changing with respect to what may be a technological dead end, but that may enable near-term science? The Center should clarify its priorities on laser development, which may be evolving with respect to whether a center legacy is a laser for existing telescopes, or technology development to enable lasers for ELTs, in order to help guide future funding decisions.

**Fast Reconstruction Algorithm:** The PAC felt that the CfAO needed to be more proactive in getting their Fast Wavefront Reconstruction Algorithms into a test phase on real hardware. LAO hardware seems an ideal place to try this out. It is fortunate that D. Gavel and B. Ellerbroek now both have workable fast algorithms, but apparently these only work so far for open loop (not closed loop).

**MEMS mirrors:** The PAC is increasingly worried about the glacial pace of AO-mirror technology improvement. We were very happy to learn that a new paradigm shift in AO for ELT’s occurred in the past year, wherein the decision was made to correct only small sub-fields within a larger field rather than correcting the entire field. This new paradigm drives AO on ELT’s toward MEMS technology for the wavefront correcting mirror, and thereby launches a new synergy with the Vision Science component of CfAO (where MEMS devices are also preferred). The CfAO is in an excellent position to exploit this newly identified synergy around MEMS technology, and to drive it forward as quickly and effectively as possible. At present, the CfAO is still very exposed in the area of MEMS mirror development, especially if a viable MEMS mirror is ever to become a key legacy of the CFAO. Now that MEMS seems to be the way forward, the CfAO should investigate ways of providing more funding for MEMS development. CfAO should capitalize on this emerging MEMS synergy between Vision Science and Astronomy and enable this common technology. The PAC was thus pleased to learn that the CfAO is already planning a MEMS workshop, and is exploring a new nanolaminates approach to MEMS fabrication using AODP funding. If necessary, the PAC wonders if CfAO may also wish to consider paying for some MEMS development out of Theme 2.

**Funding:** On MEMS, Jerry did not rule out a focused contribution from the Thirty-Meter Telescope (TMT) on MEMs technology. We recommend CfAO consider such partnering opportunities to move the technology forward. The NSF funded NOAO Adaptive Optics
Development Program (AODP) will have more funds for Theme 2 than is available through CfAO. Can CfAO play a role in this area? For example, by making connections between the multiplicity of players.

Science vs. Technology. The PAC discussed the mix of science and technology. There was some feeling that if the AO device worked the scientists would come. There was also a feeling that it is best to fund researchers who interact closely with the AO engineers at Keck and elsewhere to continually put pressure for improving the system.

Neyman's proposal: Of the various proposals that weren't funded, the PAC felt that Neyman's proposal 2.13 was most deserving of reconsideration if Keck Observatory cannot find funds. In her presentation Claire Max offered several arguments for how the requested postdoc would be an important step in the next generation of AO at Keck. If CfAO could make partial funds available, the postdoc would ideally spend part time in California in close contact with CfAO and the new Lab on AO. (Partial funding was provided to Neyman CleM)

2.2.3 Theme 3 – ExAO
Exciting developments with Gemini!
This next year is critical for ExAO, this proposal HAS to be accepted by Gemini.

The PAC was a little concerned that the extreme AO effort needs significant improvements in technology before Astronomical observations can be made. Both the actuator density and the speed of the AO system need to increase significantly before a working system can be built. The PAC wondered if there was a reasonable intermediate step, which could produce publishable Astronomical results using technology on the extreme AO road map. If this were possible, this could lead to increased support from the Astronomical community, possibly leading to new funding opportunities and a broadening of the project base. One possible approach would rely on the observation that current efforts at high contrast imaging are hampered by so called "fixed speckle", primarily due to aberrations from the telescope and instrument itself. The "fixed speckle" actually vary slowly with temperature and telescope pointing. The variation of "fixed speckle" is fast enough to preclude accurate calibration using point sources, and slow enough, that they are not eliminated by long exposure. We note that a high order deformable mirror and wavefront sensor operated at a slow rate could correct the aberrations producing these "fixed speckle", generating much smoother atmospherically limited long exposure images. Using such a system could significantly improve classical high contrast imaging while simultaneously testing the extreme AO building blocks in a relatively less challenging real world setting.

2.2.4 Theme 4 – Vision Science
The PAC continues to be impressed with the continued technology development in this theme. The participants are to be congratulated in their success in obtaining outside funding.

Dewarping of SLO: Proposal 4.9 is expected to be completed by the end of Year 6. It is therefore critical that the working code be well documented and transferred to users and future keepers of the programs in a manner that is useful. Would it be possible to include additional expertise in the program development loop?
Matlab Toolkit. CfAO can play a unique role in facilitating the development of tools that can be used by multiple groups. Typically each research group develops and maintains separate software. An example of what is possible is deblurring algorithms. The Vision Science needs are much simpler than the problems facing astronomers. A toolkit of algorithms for processing Zernike coefficients would be useful to the full community. A proposal along these lines should be encouraged for Year 7 funding. The toolkit could include things like:

- How do Zernike coefficients change as a function of pupil size and axis translation
- Go from wavefront to PSF and OTF
- Make available several metrics to go from wavefront to a measure of visual performance
- Make available several algorithms for deblurring retinal images

Intellectual property issues: The PAC discussed whether there was any possibility that future profits on ophthalmic instruments could be used to help fund the future CfAO.