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Center for Adaptive Optics
University of California, Santa Cruz

Annual Report

Program Year 2

Reporting from 1 November 2000 to 31 October 2001
Cover Photo

“High School students from the Center for Adaptive Optics’ Stars, Sight and Science. program visit the UC Berkeley School of Optometry, on a field trip. The program was offered by CfAO this summer in conjunction with the University of California Santa Cruz’s COSMOS program for talented High School students.”
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1. General Information

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1.2 Executive Summary

The Center for Adaptive Optics (CfAO), a National Science Foundation Science and Technology Center, was established in November 1999 with the mission to advance and disseminate the technology of adaptive optics in service to science, health care, industry, and education. The Center has its headquarters at the University of California at Santa Cruz, with nodes at nine other universities and one National Laboratory.

The CfAO is taking a leadership role in fostering the science and technology of adaptive optics in the US, which historically has lagged behind Europe in this increasingly important field. The Center sponsors summer schools and workshops to introduce new researchers to the field and to explore its frontiers. Its main research thrusts are in the applications of adaptive optics (AO) to astronomy (with emphasis on large ground-based telescopes), and to vision science (with emphasis on understanding human vision and on developing new technologies to diagnose and cure eye diseases).
Education is a crucial activity of the CfAO, and the integration of our research with education is an important challenge. Specific goals of our Education program are to:

1. increase the versatility of Center students and post-doctoral researchers
2. increase the number of high school students from under-represented groups who are prepared to pursue a science/technology/mathematics degree in college
3. establish a center-based model for retention and advancement of college-level students from under-represented groups
4. increase knowledge of CfAO science and technology in the broader community.

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

1. coordinating and combining research efforts to take advantage of the synergies afforded by the Center mode of operations
2. encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology
3. leveraging our efforts through industry partnerships and cross-disciplinary collaborations.
4. stimulating further investment by government and industry sources in AO research and development
5. catalyzing the commercialization of AO technologies leading to technological advancements relevant to CfAO research objectives and enabling broader use of adaptive optics.

As of the writing of this report in July 2001, the CfAO has active partnership activities with 13 optics and micro-electronics companies, 5 national laboratories, 5 non-CfAO universities (including one HBCU), 7 astronomical observatories, and 2 international partner institutions. In addition, 9 aerospace corporations are participants in a project on secure free-space communication links. This project is a direct outcome of CfAO infrastructure investments.

The first two years of the CfAO’s existence have been spent establishing strong research and education programs, and building the extensive partnerships described above. In September 2000, the Center for Adaptive Optics had a NSF Site Visit. The subsequent report, while recognizing the excellence of the science performed within the Center, identified several areas of concern. These included the need for: increased emphasis on a “Center mode of operations”, fostering stronger interactions between astronomers and vision scientists, strengthening aspects of our senior management and leadership organizations, more systems engineering, and improved education, public outreach and diversity efforts. The Center’s Executive Committee (EC) subsequently met for two days in February and developed a major new thematic approach to Center research and education. This was discussed and endorsed by Center members at a Center wide retreat in March 2001, and later to the Program Advisory Committee (PAC) and the Executive Advisory Board (EAB) who have strongly endorsed it.—See Appendix C.

In this Annual Report we will describe both our progress in Year 2 and our new thematic approach for Years 3 and following.
1.2.1 CfAO Mission and Goals
A statement of mission and goals was developed and endorsed by the Center membership in March 2001:
**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 Basis for Center re-organization
Factors identified by the Executive Committee at their 2-day retreat included the need for:
1. Greater collaboration between researchers.
2. Identification of lasting Center monuments or achievements.
3. Development of a road map with milestones to help ensure success
4. Fostering of interactions between astronomers and vision scientists.
5. Increased understanding of the Center’s educational and human resources goals on the part of all researchers and expanded opportunities to share in the achievement of these goals.

These topics formed the basis of the agenda for a Center-wide Retreat at the California Institute of Technology, Pasadena. The consensus was that these could best be achieved by reorganizing the research into an integrated thematic approach.

1.2.3 CfAO Themes
“Monuments” that the Center could achieve in its lifetime were identified and a set of themes developed to achieve them. Projects in each theme will be integrated in ways that encourage researchers to break away from the traditional “individual research investigator” mode, and instead to develop collaborative research programs.
The new Center themes are:
Theme 1: Education And Human Resources
Theme 2: AO for Extremely Large Telescopes (ELTs)
Theme 3: Extreme Adaptive Optics (eXAO), Enabling Ultra-High-Contrast Astronomical Observations
Theme 4: Compact Vision Science Instrumentation for Clinical and Scientific Use

More detailed descriptions of these Themes are provided in Section 7.

While the themes need to foster collaboration and a more focused approach to the research being undertaken, research that cuts across themes must also be encouraged. Two specific cases of this cross-cutting research feature interactions between the astronomers of Theme 2 and the vision scientists and MEMS technology of Theme 3. In the first case, astronomers with experience in image enhancement will (commencing in Year 2 and continuing into Year 3) collaborate with vision scientists to improve the quality of Adaptive Optics (AO) retinal imaging using the techniques of point spread function analysis and deconvolution. The second case applies to Center vision scientists developing AO instruments for both retinal disease diagnosis and vision correction including prescription glasses, contact lenses, and LASIK surgery. These AO instruments will need to be robust and affordable—in the $10,000 to $20,000 price range. The combination of robustness and price for AO instrumentation can currently best be achieved by the application of MEMS technology. Center astronomers working in MEMS technology are collaborating, and will continue to collaborate with the vision science team at the University of Rochester - new MEMS devices developed by the MEMS team are shipped to Rochester and tested in their new AO testbed. To date, the results have been most promising.

1.2.4 Center Oversight
In order to ensure high quality oversight, greater interaction between the Center and relevant Departments within the university, plus continuity in institutional memory, the UCSC administration and Center management have established a new Oversight Committee (previously the Director reported to the Associate Vice Chancellor, Research). Details are provided in Section 7.

1.2.5 Highlights of Research Accomplishments Year 2

Goal 1: Vision Science with Adaptive Optics
In charting the future of CfAO, scientists and engineers participating in the Vision Theme have agreed to focus their efforts on the development of ophthalmic instrumentation equipped with AO. CfAO’s long term plans call for the development of a number of prototype instruments that can be placed at many clinical sites for testing.

The two major areas in which CfAO members are applying adaptive optics to vision science are vision correction and high-resolution retinal imaging. An ongoing research program at Rochester is using adaptive optics to investigate the limits of aberration
correction for human vision. A goal of this work is to determine the ultimate benefit of customized contact lenses or refractive surgery that correct the eye’s higher order aberrations. An interesting finding is that on correction of these aberrations, the neural visual system is not equipped to take full advantage of the sharp images available to it. Capitalizing on the high resolution provided by adaptive optics in imaging the retina, Rochester and Houston have collaborated on the first measurements of the directional sensitivity of individual human cones.

To increase the accessibility of adaptive optics to the vision science community, Rochester has made its AO system available to three vision science laboratories outside of CfAO.

The Vision Science Theme of CfAO is engaged in the development of four new instruments that incorporate adaptive optics for the human eye: the Rochester 2nd Generation Flash System, the Houston Scanning Laser Ophthalmoscope, and the Indiana Coherence-Gated Camera, and the LLNL Adaptive Optics Phoropter. Two of the instruments are in operation and while none are yet appropriate for the clinic, CfAO has made major strides toward that goal this year.

Rochester and Indiana collaborated in year 2 to define the parameters of the ideal wave front corrector, given the statistics of aberrations of the human eye. To guide future improvements in corrector designs, Miller has modeled the performance of several types of commercially available correctors to compare against measured wave aberration data.

The high cost of conventional deformable mirrors is a fundamental impediment to the widespread availability of AO to vision scientists. An inexpensive and compact wave front corrector must be developed. This has become a major term goal of the CfAO. Toward this end, Rochester and LLNL are collaborating on a test bed to examine MEMS devices and an SLM for low-cost wavefront sensing. Next year, two groups will be fabricating high stroke MEMS devices for the vision application.

**Goal 1: Astronomical Science**

In year 2, a systematic characterization of the high dynamic range imaging performance of various AO systems (at Lick, Palomar, and Keck) has been performed. The long-term goal is to identify the optimization of those AO systems and their suitability for imaging protella disks and other companions to stars. Activities have also focused on improving the analysis routines; a lack of understanding and reliable modeling of AO point spread functions have plagued many AO science programs. This year has also resulted in the first statistically-significant sample of faint distant galaxies observed with AO. This allows detailed comparisons between this sample (at redshift z~0.5) and local samples of galaxies. The results are consistent with theories that most galactic disks were in place significantly earlier (probably by z~1) and have continued to grow by modest accretion of new material.

While Year 1’s activities were focused on “imaging” data from Keck and Gemini, in Year 2 this was expanded to include the challenge of obtaining the first spectroscopic
observations of the central 1 arcsec$^2$ located near our Galaxy's central supermassive black hole. This provided data to determine the spectral types and radial velocities for the stars in this critical location.

Images and spectra were also obtained for Titan, Neptune, Uranus, and Io. A major effort was expended on testing and comparing several methods (MISTRAL, IDAC, Lucy-Richardson) to enhance a posteriori the sharpness of the images and correct for aberrations caused by the use of extended reference sources. Spatially-resolved infrared spectral measurements of Saturn's moon, Titan, revealed the presence of Tropospheric clouds at the South Pole. Because atmospheric methane in Titan's atmosphere acts as an altitude discriminant, the discovery of high geometric albedo at the tropospheric altitude suggests methane condensate. This discovery only came about through the integrated coordination of planetary scientists and AO instrument builders.

**Goal 2: Bringing Adaptive Optics to the Broad Community**

This goal has two major components: Summer schools and workshops, and dissemination and development of methods and software tools for analysis of AO images.

The summer school held July 2000 was a great success, with over 100 participants. The summer school being held this month (August 2001) will be on more advanced topics of AO and it will have approximately 100 participants, the maximum allowed. This advanced workshop will include computer labs for real data reduction, mathematical tools, and other topics.

The CfAO has sponsored 15-20 workshops each year on all aspects of AO, including very specific ones on the analysis of AO data and point spread function (PSF) estimation.

The peculiar PSF of AO images requires special attention during data analysis, as this PSF can vary with time and field angle. Thus calibration and accurate assessment of the PSF are critical for many programs. These techniques are not as yet well known in the general community. We have worked on blind deconvolution algorithms that internally estimate the PSF from multiple exposures. This has now been successfully applied to planetary images and less successfully to images of the galactic center. The software is now available on the CfAO website. Another software package, StarFinder, has been modified to accommodate spatially varying PSF’s. Application to AO images appears very encouraging.

We have begun work to determine the PSF from real-time telemetry data from the AO system itself. This work is using the excellent telemetry data sets from the Palomar AO system.

Software related to AO data reduction is now available at the CfAO website, which currently contains seven packages.
Image processing algorithms are applicable to vision science as well as astronomy and collaborations between Center members are underway to explore the potential of sophisticated software to enhance the quality of AO images of the human retina.

**Goal 3: Development of Advanced Instrumentation for Adaptive Optics**

In vision science, the CfAO is developing a scanning laser ophthalmoscope for three-dimensional optical sectioning of the human retina. This should produce its first images of the retinal region by the end of year 2. The Center is also developing a more challenging instrument, a coherence gated camera to achieve better contrast and finer sectioning of the retina. Both of these instruments require AO systems that are being built, based on experience with the AO system at Rochester.

In astronomy, the next exciting horizon is to perform spectroscopy at every spatial location in an AO image. The OSIRIS integral field spectrograph passed its preliminary design review for the Keck Telescope. Center funds were essential for building a test bench for this instrument and developing data reduction algorithms. Integral field spectrographs intrinsically produce very complex data products due to the presence of over 1000 slightly overlapping and staggered spectra on the same detector. An efficient and accurate data reduction algorithm was a critical development necessary to gain approval for project continuance. The OSIRIS team leader, discussed the problem with other center members, and determined that it was mathematically very similar to the process of iterative matrix inversion used for deformable mirrors. Two algorithms were developed through this unexpected collaboration and were tested by the OSIRIS team. One based on Gauss-Seidel iterations has proven very successful and is much more efficient than the original requirement for the instrument. This algorithm along with Center sponsored development of hardware and Center interactions have successfully leveraged a $4 million project for a facility instrument with the world's largest adaptive optics system.

The AO spectrograph for Lick Observatory being developed by the Center has now had its first tests with starlight and the silicon grisms. The CfAO faculty are also developing a coronograph for use with this spectrograph.

**Goal 4. – Advanced Adaptive Optics**

The fourth goal of the CfAO is to pursue advanced technologies that will make the next generation of adaptive optics systems more powerful, more versatile, and/or less expensive. Highlights of CfAO accomplishments toward this Goal in Year 2 are described here.

1) **MEMS deformable mirrors:**

The CfAO is spearheading a large collaborative activity to produce high-optical-quality MEMS deformable mirrors for use in vision science and astronomy. In Year 2 the Center evaluated several new MEMS devices in our testbed. We found that a 140-actuator MEMS mirror made by our partners at Boston University had the best surface quality (30 nm rms after flattening) combined with a stroke suitable for astronomical applications. BU is now designing a next-generation device with 1024 actuators.
Vision-science applications of adaptive optics need deformable mirrors with higher stroke: 8-12 microns would be optimal. Working closely with CfAO’s vision scientists, a UC Berkeley graduate student produced an optically excellent MEMS mirror (< 6 nm rms) with a stroke of 6 microns, and has now extended this design to 12-micron stroke for vision science.

2) Laboratory testbeds for ultra-compact deformable mirrors:
The CfAO has completed three test-beds where new MEMS and liquid crystal deformable mirrors can be thoroughly evaluated in closed-loop AO systems. Testbeds at the University of Rochester and LLNL were completed in Year 2 under CfAO funding; a third testbed at Lucent Technologies was completed under parallel Lucent funding. These facilities provide crucial infrastructure for developing advanced AO applications. This year two new projects were enabled by our testbeds. 1) A prototype ultra-compact AO system is being built at the LLNL testbed, and will be used at the UC Davis Ophthalmology Department to test the limits of human acuity. 2) A national consortium has been formed to develop clinical ophthalmic instruments based on MEMS AO, and to test these instruments in specific diagnostic protocols for diseases that cause blindness. Both projects are being supported with new external funds obtained as a result of CfAO’s basic infrastructure investment in AO-testbed and MEMS test facilities.

3) Advanced laser technology:
If only natural stars are used to measure the turbulence in the earth’s atmosphere, less than 10% of the sky is accessible to high-quality AO correction at near-infrared wavelengths. Even smaller fractions are accessible at visible wavelengths. Laser guide stars can remedy this by creating artificial stars or “beacons” almost anywhere in the sky. The CfAO is pursuing two approaches to developing new lasers for sodium-layer guide stars. Both projects use sum-frequency schemes to generate 589 nm laser light, and are highly leveraged with our partner institutions, since new laser development and engineering is quite expensive. Both projects involve industrial partnerships, and one is in collaboration with both an international partner and a collaborating faculty member from an HBCU. Substantial progress was made on both projects in Year 2.

The goal of the first laser project is to produce a diode-pumped solid-state pulsed sum-frequency laser for use at an astronomical observatory. This University of Chicago project is co-funded by the CfAO and the Gemini Observatory (a CfAO partner institution), in an industrial partnership with LiteCycles, a Tucson, AZ-based laser company. This year the first of two gain modules was completed, and testing is about to begin as of July 2001. The optical bench and housing for the two gain modules and the sum-frequency module were completed in Year 2, as was fabrication of the sum-frequency module.

The goal of the second laser project is to develop a new fiber laser for laser guide star applications. The heat-dissipation characteristics of fiber lasers, their excellent efficiencies and spatial mode characteristics, and their use of commercial telecommunications components make them desirable for high power applications. This
laser is based on a new sum-frequency mixing scheme: combining an Er:doped fiber laser operating at 1583 nm with a 938 nm Nd:silica fiber laser, to generate 589 nm light. The 938 nm fiber is a novel device in which losses due to amplified spontaneous emission (ASE) must be suppressed. This year we identified four methods to suppress ASE, and showed via lab tests and computer simulations that they should be sufficient for the guide star application. We developed partnerships with the European Southern Observatory to participate in building and testing this laser, and with a faculty member from Hampton University, an HBCU, to test methods of ASE-suppression and to evaluate new sum-frequency crystals.

4) Adaptive optics for Extremely Large Telescopes
The National Academy of Sciences’ decadal study on astronomy and astrophysics has recommended design and construction of a 30-m “Giant Segmented Mirror Telescope.” The adaptive optics system for such a telescope will incorporate features significantly more sophisticated than those used today. Use of several laser guide stars to probe the whole volume above the telescope will greatly reduce the “cone effect” due to the finite height of the laser guide star in the atmosphere. In addition multiple guide stars will increase the corrected field of view of the adaptive optics system, since a larger volume of turbulence can be measured by placing the lasers farther apart. This method is sometimes called turbulence tomography. To correct the larger volume several deformable mirrors are needed, each optically conjugated to different heights in the atmosphere. This is called multi-conjugate adaptive optics (MCAO).

In Year 2 the Center studied fundamental questions related to the implementation of MCAO on extremely large telescopes. To accomplish this we developed and tested an end-to-end MCAO computer simulation code, in collaboration with Gemini Observatory (one of the CfAO’s partner institutions).

When several laser guide stars are used, the tilt indeterminacy inherent in laser beacons manifests itself as low order modes (defocus, astigmatism) which cannot be measured by the laser guide stars. In Year 2 we investigated two potential solutions: Method 1) uses a faint natural guide star from which tip, tilt, defocus, and astigmatism are measured; Method 2) uses 3 or more natural guide stars, from which only tip and tilt are measured. We characterized the pros and cons of each approach, and concluded that Method 2) is more appropriate if highly stable AO correction is needed, whereas Method 1) yields higher correction quality in the center of the field, but decays more rapidly at the edge of the field of view. In addition Method 2) can be used with fainter stars.

Education and Human Resources
In support the CfAO’s long term commitment to fully integrate research and education, Education and Human Resources has undergone a major restructuring in Year Two. Several new projects were started in Year Two including –

*The first professional development conference for Center graduate students and postdoctoral researchers.* This was designed as a mechanism for building community, starting new cross-disciplinary collaborations, and integrating this group fully into Center
activities. The conference was held in Kona, Hawaii and included tours of Keck and Gemini Observatories – a highly valued experience. The participants also generated non-technical posters that were presented to local science teachers, and are now being distributed for use in classrooms in both Hawaii and to schools local to the CfAO headquarters in Santa Cruz. Half of the conference time was dedicated to giving participants a hands-on experience with inquiry-based learning. Many of whom felt that this experience had changed the way they thought about teaching and learning. One of them subsequently implemented inquiry techniques into a CfAO educational activity and will discuss the success of this at the upcoming CfAO Summer School. The conference indicated the strong interest that CfAO graduate students and postdoctoral researchers have in education and has generated a momentum within the CfAO to develop education that is based on standards and grounded in educational research.

Another project during Year Two was the development of a partnership with Watsonville High School. Watsonville High is located approximately 30 miles from UC Santa Cruz and has a student body that is 85% Hispanic, and a college-bound rate far below the state average. This summer Watsonville High students participated in the newly developed course cluster, Stars, Sight and Science, which included three courses: astronomy, vision science, and science communication. A Watsonville High science teacher worked with CfAO members to develop and teach the course, and will continue her involvement through the Paired Mentoring Program that starts in Year Three. Four other Watsonville High teachers will also participate in the Paired Mentoring Program. Stars, Sight and Science involved many CfAO members and nodes and provided students with an experience that closely mirrored “real science”. Using a project-based approach, students investigated multi-disciplinary topics in science, and were exposed to possible careers in science for the first time. Contact will be maintained with these students through the Paired Mentoring Program and other academic year activities.

1.2.6 Closing remarks
This second year of the CfAO has been extremely successful, with a very productive research program, involving significant cooperative efforts among its members. The education and outreach programs are now focused and coherent, thanks to the efforts of our Associate Director of EHR, Lisa Hunter. Industrial partnerships are growing, and the plans for Year Three will significantly increase the “practical” efforts of the Center. We are learning that it takes significant time and effort to make the Center more than the sum of its parts, but the progress towards the greater objectives of STC’s is significant and also rewarding.
2. Research
2.1 Goal 1 – Vision Science with AO, Personnel and Research Narrative

<table>
<thead>
<tr>
<th>GOAL 1 - VISION SCIENCE WITH AO</th>
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<tr>
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Research Narrative – Vision Science with AO

In charting the future of CfAO, scientists and engineers participating in the Vision Theme have agreed to focus their efforts on the development of ophthalmic instrumentation equipped with AO, leading hopefully to commercialization. This decision was prompted in part by the NSF site visit report on the first year’s progress in which the Center was encouraged to make AO technology for the eye more widely accessible, especially to clinical researchers. Ultimately, broad accessibility requires the development of low-cost, compact, and robust devices that can be used by clinicians who are unskilled in adaptive optics. There is good evidence of the scientific value of adaptive optics for the eye but its ability to aid in the diagnosis and or treatment of retinal disease has not been established. The best way to establish clinical utility is to make AO systems available to clinical researchers and enable them to gain experience with this technology. CfAO’s long term plans call for the development of a number of prototype instruments that can be placed at many clinical sites.

The NSF site visit report also encouraged the Center to have more interaction between vision science and astronomy. The decision to structure our goals around technology instead of science was prompted by the synergy that CfAO can create between vision scientists and astronomers who share an interest in AO technology. The focus on instrumentation will not diminish the Center’s scientific contribution to vision research, since many participants in the Vision Theme are primarily scientists. Moreover, CfAO has funded the development of new AO instrumentation that will make possible science that would otherwise be impossible to conduct. The technical infrastructure created by the Center has leveraged additional funding, such as the recently funded DOE Biomedical Engineering Grant that binds LLNL, Rochester, and three partners outside CfAO (Sandia Laboratories, Willmer Eye Institute, and UC, Davis) in a collaborative effort on adaptive optics for clinical research applications. Most of the year 2 scientific results described here were obtained through the support of additional grants as well as CfAO, including Rochester’s grant from the National Eye Institute. CfAO provides the funding for hardware and engineering support that has been critical to the success of these scientific endeavors.

The two major areas in which CfAO members are applying adaptive optics to vision science are vision correction and high resolution retinal imaging. There have been interesting new developments in both areas last year, and these are described below.

2.1.1 Improving Vision With Adaptive Optics

The correction of the eye’s monochromatic aberrations with adaptive optics has demonstrated the ability to increase visual performance even in people with normal vision. This discovery has lead to considerable corporate interest in the development of contact lenses and laser refractive surgical procedures that might provide patients with improved vision compared with current technology. Bausch and Lomb, a CfAO corporate partner, is investigating both these concepts. They are exploring the possibility of fabricating customized contact lenses that correct higher order aberrations as well as the defocus and astigmatism corrected by conventional lenses. They are also collaborating with the University of Rochester on clinical trials of Bausch and Lomb’s Zyoptix laser
system to determine whether iatrogenic aberrations induced by the laser refractive surgery can be reduced and whether patients’ higher order aberrations can be corrected. CfAO is continuing to play a valuable role in this corporate relationship by enhancing capabilities for testing vision after various aberrations have been corrected by adaptive optics. An ongoing research program at Rochester is using the adaptive optics technology under development with CfAO funding, to investigate how far aberration correction can extend the limits of human vision.

In most normal eyes, the benefit of correcting higher order aberrations is small. For example, in the average person, aberrations of third order and higher blur the retinal image by an amount approximately equivalent to 0.3 diopters of defocus. To put this figure in perspective, most clinicians refract the eye to the nearest 0.25 diopters in prescribing glasses. However, a population study conducted with CfAO support last year showed that, just as certain individuals suffer from astigmatism while others do not, there are some people that have unusually large amounts of 3rd order aberrations and higher. Such individuals stand to gain more from customized contact lenses or refined refractive surgical procedures that correct higher order aberrations.

![Figure 2-1 Improved Acuity with Adaptive Optics](image)

Observers have noted that after correcting higher order aberrations with adaptive optics, there is an improvement in subjective image quality, the extent of which varies from subject to subject. Rochester investigators measured acuity for letter targets delivered
with and without adaptive optics. Subjects were asked to identify the orientation of the letter E, presented in one of four orientations corresponding to rotations of 90 deg. The threshold was determined as the minimum size of the letter whose orientation subjects could correctly identify. The Figure 2-1 above shows the results of three subjects. The left bars indicate the minimum resolved width of the letter when defocus and astigmatism were corrected, the middle bars show improved acuity when higher order aberrations were corrected with adaptive optics, and the right bars show even more improvement when chromatic aberration were avoided. Adaptive optics clearly provides an improvement in acuity with large pupils, with 2 of the 3 observers approaching 20/10 acuity in monochromatic light.

![Figure 2-1](image)

**Figure 2-1** – Improvement in acuity with adaptive optics

Despite the improvement gained with adaptive optics, recent evidence obtained using Rochester’s 2nd generation adaptive optics system that was designed and constructed with CfAO support, has revealed neural limits on to the improvement of vision by correcting higher order aberrations. In experiments to measure visual acuity for letters seen with adaptive optics, subjects report that the 20/20 letter E, for example, appears less clear when viewed through a 6 mm pupil with adaptive optics correction than when viewed through a 3 mm pupil with or without adaptive optics. There is also supportive evidence from the wavefront sensor as well as retinal images acquired with the same instrument, that the AO system is providing substantially better image quality with a 6-mm pupil than with the 3 mm. However, though the apparent contrast of the letter is clearly increased, the same letter if viewed through a 3 mm pupil looks less clear when the luminance is compensated to match that at the 6 mm pupil level. Corroborating this anecdotal

![Figure 2-2](image)

**Figure 2-2** – Reduction in AO efficacy at lower pupil size
evidence are measurements of visual acuity as shown in Figure 2-2 for three subjects. Though adaptive optics increases acuity, it does not produce a better performance than that obtained with 3 mm pupils, suggesting that the visual system cannot take full advantage of the additional sharpening provided by adaptive optics in conjunction with a 6 mm pupil. This may reflect the sampling limitations of the foveal cone mosaic or subsequent neural limitations in the visual pathway. It is intriguing that the conditions that produce the most perfect retinal image of a letter don’t necessarily yield the clearest perceptual experience. One interpretation of these results is that each individual’s vision system develops to take in account the optical aberrations of the eye. When these aberrations are corrected, the visual system is not equipped to resolve the sharp images available to it.

![Cone Disarray Projected into the Pupil Plane](image)

**Figure 2-3 – Cone Disarray**

### 2.1.2 First Measurement of Directional Sensitivity of Individual Human Cones.

The Stiles-Crawford Effect (Stiles & Crawford, 1933) describes the reduction in apparent brightness of light as its entry point moves from the center to the edge of the pupil. The Stiles-Crawford effect, measured psychophysically by stimulating large numbers of cones, is a combination of the waveguide properties of single photoreceptors and the disarray in individual cone pointing direction. While indirect methods (Burns, Wu, Delori, & Elsner, 1995; MacLeod, 1974) have been used to infer the relative contributions of cone angular tuning and disarray to the overall Stiles-Crawford effect, it has not been possible to disentangle these factors with direct measurements in the human eye. A collaborative effort between Houston and Rochester has succeeded in measuring the angular tuning properties of individual human cones for the first time, and the disarray in individual cone axes that contributes to the angular tuning properties of the retina as a whole. By collecting images of the same patch of cones when the patch is
illuminated through different points in the pupil, one can measure the pointing direction and breadth of tuning of each cone in the image. Figure 2-3 above shows the pointing direction of each cone relative to the center of the pupil for two subjects. For each subject, all the cones are tuned very closely to the same direction. The disarray in cone pointing direction is very small compared with the width of the tuning function for a single cone. This shows that the Stiles-Crawford effect is a good approximation of the angular tuning of single cones.

2.1.3 Increasing the Accessibility of Adaptive Optics to the Vision Community.
A major goal of the CfAO is to increase the accessibility of adaptive optics to vision scientists generally. Rochester is now making its adaptive optics system available to three groups of vision scientists outside the Center.

1. The Role of Higher Order Aberrations in Accommodation. Phillip Kruger, SUNY College of Optometry. The human eye is remarkably good at choosing the correct direction to change focus when the distance of a visual stimulus is either increased or decreased. The error signal used by the visual system to guide accommodation is not understood. Chromatic aberration seems to provide some information. It is also possible that monochromatic aberrations can play a role and this theory is only now directly testable, because the aberration structure can be controlled with adaptive optics. Kruger has visited Rochester to conduct feasibility experiments, and will return this fall to collect additional data.

2. Circadian Migration of Cones in Fish Retina. Ellis Lowe, Cornell University. Researchers at Cornell have circumstantial evidence that the cone mosaics of certain fish such as the walleye, change from a square to a triangular packing geometry and back again every 24 hours. The functional significance of this bizarre transformation is unknown. The CfAO is in an excellent position to confirm and study this phenomenon, because we believe we can noninvasively image receptors and track changes over time in individual fish. Cornell scientists have made two visits to Rochester for these experiments, and additional visits are planned for the fall.

3. The Topography of the Cone Mosaic in Humans with Known Photopigment Gene Arrays. Jay and Maureen Neitz, Medical College of Wisconsin. Jay and Maureen Neitz are leading experts in relating the genes that code for the cone photopigments to visual performance. They are using the Rochester AO system to determine the arrangement of the different kinds of cones in people with unusual kinds of color vision. For example, they have identified and Rochester plans to image the retina of a woman who suffers from two kinds of color blindness simultaneously. One of her two X chromosomes causes a form of red-green color blindness known as protanopia and the other causes deuteranopia. If adaptive optics can be used to visualize the packing arrangement of her cones, we may better understand how color vision and the trichromatic cone mosaic develops. Rochester has made significant improvements in its 2nd generation adaptive optics system that will greatly increase the probability that these experiments will succeed.
By its support of post-docs with expertise in AO engineering who operate, maintain, and enhance this instrument, CfAO funds the technical infrastructure at Rochester, enabling these collaborations.

### 2.1.4 Progress on Vision Science Instrumentation

The CfAO Vision Science Theme is engaged in the development of four new instruments that incorporate adaptive optics for the human eye - the Rochester 2nd Generation Flash System, the Houston Scanning Laser Ophthalmoscope, the Indiana Coherence-Gated Camera, and the LLNL Adaptive Optics Phoropter. Two of these devices are already operational and substantial progress has been made on the other two. The development of the instruments, though undertaken at four different sites, is by no means independent. CfAO has provided the forum not only for sharing ideas about how to build better instruments, but also for sharing tangibles. For example, Indiana and Rochester shared the cost of a 37 channel deformable mirror and driver and Rochester provided Houston and Indiana with their mirror control software. LLNL has provided valuable advice to Rochester about optimizing the mirror control loop in its 2nd Generation AO system. Not only have we been able to share in a number of ways, we have also been able to avoid redundancy. The open communication provided by CfAO ensures that different sites do not suffer the inefficiency of doing the same experiment unintentionally. There is no doubt that this level of cooperation would not have arisen without CfAO binding the efforts together in a single coordinated enterprise.

An essential step toward the CfAO goal of increasing the accessibility of adaptive optics is the development of compact, inexpensive AO systems that can be used in clinical environments. These environments do not generally have any optical engineering support and ultimately, adaptive optics will not be useful unless it can be incorporated in turn-key, robust instruments that can be operated by a technician with minimal training. While the instruments discussed below are not ready for the clinic yet, CfAO has made major strides toward that goal in Year 2.

### 2.1.5 Completion of University of Rochester’s 2nd Generation Adaptive Optics System for the Eye.

Details of this system and its performance recently appeared in Optics Express (Hofer, et al. 2001). The key improvements in the new system over the 1st generation are:

1. Real-time closed-loop feedback control (30 Hz frame rate, 0.8 Hz closed-loop bandwidth).
2. A 97 actuator deformable mirror replaced a 37 actuator mirror in generation 1.
3. A more robust and accurate wavefront sensor.
4. A CCD camera for retinal imaging with 2.7 times the quantum efficiency of the old system.
5. A completely automated experimental protocol.

While an AO system operating with a closed loop bandwidth of 0.8 Hz may not seem impressive by the standards of current astronomical AO systems, it represents a critical step forward for vision science. The mirror control system does not require special purpose hardware and all computations are performed on a personal computer. In the 1st
The 2nd generation adaptive optics system at Rochester, it took approximately 30 minutes to correct the wave aberration. The 2nd generation system can correct the eye's aberrations in 250-500 msec and reduces by a factor of 5 the number of images required for the same signal to noise ratio. This enables Rochester to run experiments much more quickly and efficiently, with successful imaging on a larger fraction of subjects. The system provides dynamic correction of fluctuations in Zernike modes up to 5th order. Correction of the temporal variation in the eye's wave aberration increases the Strehl ratio of the point spread function nearly 3 times and increases the contrast of images of cone photoreceptors by 33% compared with images taken with only static correction of the eye's higher order aberrations. The system can reduce the eye's residual rms wave-front error over a 6.8 mm pupil to values as low as 0.1 microns.

Figure 2-4 – Schematic of 2nd Generation AO system layout at Rochester
The improvement in retinal image quality provided by correction of the eye’s higher order aberrations with the AO system is illustrated in Figure 2-6 below. This figure shows two representative images of the same retinal location taken on the same day for one subject with and without AO. This particular subject has superior optical quality, compared to the majority of subjects, yet there is still a dramatic improvement in the quality of the retinal image taken with AO. Cones that are barely detectable in the first image are clearly visible in the second.

Figure 2-6 Single representative retinal images for one subject b) with and a) without AO. The location is 1.25 degree eccentricity on the temporal retina. The subject’s refractive error was corrected to optimize the quality of the retinal image for the image taken without AO.
To quantify the improvement in retinal image quality provided by the ability to correct dynamically we compared image power spectra. The figure 2-7 below shows the improvement in the retinal image power spectrum (ratio of the image power spectrum with dynamic AO to the image power spectrum with only static correction of higher order aberrations) averaged across 5 subjects. The range of cone frequencies for these subjects is indicated on the plot. At these frequencies the average improvement in the retinal image power spectrum is almost a factor of two.

2.1.6 Completion of University of Houston’s Adaptive Optics Scanning Laser Ophthalmoscope
To meet the CfAO goal of making adaptive optics accessible to the clinical research community, we are developing imaging systems beyond the flash imaging camera at Rochester that have enhanced capabilities for viewing the retina. Confocal scanning, when combined with adaptive optics, promises to increase the axial resolution of retinal images nearly 10-fold. This offers the exciting prospect of allowing individual layers of the retina to be sectioned optically and the 3-D volume of the retina to be rendered. The University of Houston has completed the construction of the adaptive optics scanning laser ophthalmoscope (AO-SLO) and obtained the first AO assisted, real-time images of the human retina. The device development has been funded by CfAO, and the science to be performed with the instrument will be funded by the National Eye Institute. Future goals are to explore reflectance properties of photoreceptors in the human eye and continue to develop and improve the optical design of the AO-SLO.
The University of Houston’s most recent AO correction of a human eye reduced the rms wave front error over a 7 mm pupil from 0.6 to 0.127 microns. This is a sufficient reduction in aberrations to allow photoreceptor imaging. The figure 2-9 below shows the drop in the wave front rms error with each frame of the AO correction for a 7, 6 and 5 mm pupil.
Houston has obtained their first AO-corrected images in the AO-SLO. The images shown in Figure 2-10 are of a model eye where the optics are a 30 mm focal length lens and the “retina” is a microchip (used to provide a sample with microscopic detail). The images show a detail of the microchip from an area of about 0.75 mm square. The left image shows the best detail obtained with a focus correction only. The right image shows the same object after AO correction. The RMS aberration in the AO-corrected image was about 0.03 microns.

![Without Adaptive Optics](image1.png) ![With Adaptive Optics](image2.png)

**Figure 2-10** – Test Result showing improved resolution possible for retinal imaging with AO

### 2.1.7 The Optimal Pupil Size in the Human Eye for Axial Resolution

One of the considerations in designing a confocal imaging system for the eye is to determine what pupil size maximizes resolution given the wave aberration of typical eyes. The point spread function can be calculated in 3 dimensions. The narrowness of the PSF in the lateral dimension governs the lateral resolution. The axial extent of the PSF near the focal plane governs the depth of focus and potential axial resolution in the Scanning Laser Ophthalmoscope. It is well known that the optimal pupil size for lateral resolution is between 2 and 3 mm but it is less clear what the optimal pupil size is for axial resolution when the eye’s optics are left uncorrected.

To calculate this, Roorda and his colleagues at the University of Houston measured the wavefront aberrations of 16 eyes and calculated their 3-D PSFs. Axial resolution was computed as the full-width at half-max of the intensity that would be detected in a confocal scanning laser ophthalmoscope, if a diffuse object were moved axially through the focal plane of the aberrated objective lens. (In a scanning laser ophthalmoscope, the objective lens is the optics of the eye). They determined that the pupil size that gives the narrowest optical section varies greatly between individuals and on average is about 4 mm, which is greater than for optimal lateral resolution. Since Houston is primarily
interested in confocal imaging with adaptive correction, a 4 mm pupil is a lower bound on the pupil size for optimum axial resolution.

2.1.8 Indiana University’s Progress on the Coherence-Gated Retinal Camera

Indiana University is moving forward on the Coherence-Gated Retinal Camera. This instrument, when completed, will provide an alternative method to confocal scanning as a way to optically section the retina. CfAO is supporting the development of this device as part of its major goal to demonstrate the value of adaptive optics in clinical research. Coherence gating is a form of low-coherence interferometry that relies on the short temporal coherence of the light source to optically section thin 2-D slices of 3-D semi-transparent objects (e.g. human retina). Exceptional axial resolution can be achieved with spectrally broad sources, complementing the high transverse resolution gained with adaptive optics. In year one and early year two, a prototype coherence-gated camera was constructed for evaluation on artificial eyes. The camera was realized with a Michelson interferometer whose principal components included a spectrally-filtered incandescent or LED light source, crossed linear polarizers in reference and object channels, and a quarter waveplate, rotatable linear polarizer, and CCD camera in the detection channel. Controlled rotation of the detection polarizer created known phase-shifted delays between the reference and object beams, which were recorded with the CCD camera. 2-D optical sections of test objects were reconstructed from the phase-shifted images. This design provided good optical sectioning, but the reconstruction quality was limited by non-linear distortions and intensity fluctuations across the phase-shifted images induced by the rotatable polarizer and quarter wave plate. Furthermore, the narrow spatial coherence of the incandescent source made alignment of the reference and object beams extremely tedious and impractical for use with the eye.

Using the experience gained with the prototype system, Year Two centered on re-engineering an improved coherence-gated camera. This new camera overcame the problems encountered previously and was designed to collect retinal images in living eyes. The re-engineering involved: (1) determination and implementation of a sufficiently powerful and spectrally desirable low-coherent light source for illuminating the retina, (2) integration of a very fast and accurate translator for axial movement of the reference mirror.

Also in Year Two, an adaptive optics system for the coherence-gated retina camera was successfully constructed and tested. The AO system consisted of a 37-actuator PMN Xinetics mirror and a Shack-Hartmann wavefront sensor. The mirror and control software were obtained from Rochester when Rochester upgraded its system to 97 channels, thus capitalizing on cooperation within the CfAO. The figure 2-11 shows the optical layout of the AO retina camera under construction at Indiana University.
2.1.9 LLNL Adaptive Optics Phoropter

The ongoing development of an adaptive optics phoropter is an excellent example of the effectiveness with which CfAO fosters collaborations between astronomy and vision science that would otherwise never have occurred. Lawrence Livermore, whose previous expertise in adaptive optics has been primarily in the domains of astronomy and high-energy lasers, is collaborating with Bausch and Lomb, UC Davis, and the University of Rochester to develop an inexpensive AO system for the eye. This device will allow a patient to view a visual acuity chart through adaptive optics. The AO system will automatically measure and correct the aberrations of the patient’s eye and will provide a prescription for glasses, contact lenses, or a refractive surgical procedure. We anticipate this device will be more accurate than either current autorefractors or the age-old subjective method of asking the patient to report which target looks clearest. Also, it will provide information for customized correction of aberrations beyond defocus and astigmatism. Moreover, the DM in the system will enable the patient to appreciate the visual benefit of a prescription at the vision testing phase. An instrument is nearly finished that will be deployed at the UC Davis Department of Ophthalmology. LLNL will build a second instrument to be tested at B&L and at Rochester. Bausch and Lomb has committed $120K toward this project and is participating in discussions of instrument design. This collaborative effort illustrates the cooperation between corporate, government, and university partners and between astronomy and vision science, that
CfAO has already engendered. Our future plans make it clear that this cooperation is destined to increase.

2.1.10 Toward the Next Generation of AO Instruments for the Eye

An Optimized Wavefront Corrector for Vision Science

The correcting device for vision applications needs the characteristics required for diffraction-limited imaging to be defined. These include the actuator number, stroke, and spacing. Corrector optimization is critically important for the development of less expensive, more compact, and more powerful devices and is essential for the widespread use of adaptive optics in ophthalmic instruments. Rochester and Indiana collaborated in Year 2 to define the parameters of the ideal wave front corrector given the aberrations of the human eye. The recommended parameters in the table below are based on two studies of the wave aberration of large populations of human eyes, firstly for the 5.7 mm pupil by Jason Porter at Rochester and for a 6.8 mm pupil from the University of Indiana, courtesy of Hauwei Zhao.

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<th>Temporal Bandwidth</th>
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<td>Mirror Stroke</td>
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<td>Flatness</td>
<td>&lt;30nm rms.</td>
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<tr>
<td>Geometry</td>
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<td>Actuator Coupling</td>
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<tr>
<td>Reflectivity</td>
<td>&gt;80% (400-900nm)</td>
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<tr>
<td>No of actuators across the pupil</td>
<td>17x17 (assuming continuous faceplate)</td>
</tr>
<tr>
<td>Size (diameter)</td>
<td>4-8mm i.e. comparable to pupil size</td>
</tr>
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</table>

To guide future improvements in corrector designs, Indiana University has modeled the performance of several types of commercially available correctors in conjunction with measured wave aberration data.

In Year One, we modeled the performance of piston segmented devices, which include liquid crystal spatial light modulators and micro-mirror arrays. Results predicted that a 100x100 element liquid crystal device is needed to achieve diffraction-limited correction across the maximum physiological pupil size of 8 mm. $2\pi$ phase wrapping was found to be acceptable for these devices, even in polychromatic light. The chromatic aberration inherent in the human eye was found to be substantially larger than that produced by phase wrapping or material dispersion (e.g. liquid crystal) of the corrector.
Figure 2-12 Wavefront corrector types applied to the human eye in the laboratory. Correctors (column 3) are grouped according to their actuator influence function (column 1). Experimental results have been cited in the literature covering a random mix of actuator number (column 4) and actuator stroke (column 5). The performance of piston segmented devices was modeled at Indiana in year one of the Center; Gaussian and Poisson devices were modeled in year two (column 2).

In Year two we extended the modeling to include continuous faceplate correctors and a larger database of wavefront measurements that were collected on 100 subjects at Indiana University in 2000. The database was funded by a NEI-STTR Phase I grant. We evaluated four wavefront correctors that are commercially available: (1) 13-electrode Sydney University bimorph, (2) 19-electrode University of Hawaii bimorph, (3) 37-actuator Xinetics, and (4) 97-actuator Xinetics. In addition the influence of actuator stroke, ranging from zero to infinity, was included in the model. Predicted performance of the commercial correctors is shown in Figure 2-13. The correctors were optimized to minimize the RMS of the residual wavefront using a least squares method. Pupil diameter was 7.5 mm at the eye with correction over the central 6.8 mm. The results show that all manufactured mirrors decreased the wavefront RMS. None on average provided diffraction-limited imaging. The best performing mirror was the 97 Xinetics whose RMS was almost half that of the other three mirrors. Increasing actuator stroke improved the performance of the 37, but not the 97 Xinetics mirror. For the bimorphs, increasing stroke beyond the ±11 µm already available in the commercial devices yielded no improvement.
Figure 2-13 Predicted average performance of two bimorph and two Xinetics mirrors for correcting the wave aberrations measured in 70 normal right eyes. The aberration data was obtained from the Indiana Aberration Study. Pupil size was 7.5 mm with correction over the central 6.8 mm. Wavelength was 0.633 µm. Manufactured electrode/actuator stroke for the bimorphs and Xinetics were ±11 µm and ±2 µm, respectively.

2.1.11 The Rochester Test Bed for Low Cost Wave Front Correctors

The high cost of conventional deformable mirrors is a fundamental impediment to the widespread availability of AO to vision scientists and to the clinical community. Conventional deformable mirrors, such as those made by Xinetics, cost about $1,000 dollars per actuator. With roughly 100 actuators required in a vision AO system, the deformable mirror by itself makes an ophthalmic instrument prohibitively expensive. Moreover, these mirrors are large, greatly increasing the size of ophthalmic instruments and consequently, a typical examination room would not accommodate such a large instrument. An inexpensive and compact wave front corrector must be developed. This has become a major long term goal of the CfAO.

The first step in developing such a wave front corrector is already under way this year. In a collaboration between LLNL and Rochester, two alternative wave front correctors are being tested at Rochester. A Hamamatsu spatial light modulator (SLMM X7550), a Boston Micromachines MEMS mirror, and a 97 actuator Xinetics mirror are being evaluated using metrics based on interferometry, wave front sensing, retinal imaging, and vision improvement. The 2nd generation AO system is serving as a test-bed for these new technologies. It has been designed to easily switch between any of the three wave front correctors.

A key feature of the SLM is that it is not pixelated, so that diffraction by individual pixels can be avoided. Moreover, it has a resolution of 644 by 484, far higher than a conventional DM enabling very high order aberrations to be corrected. Its size is small
(1.3 inches diagonally) which is needed for a compact, commercial instrument for a physician’s office. Because the device is based on LCD technology, it can for large quantities, be made cheaply compared with conventional monolithic mirror technology. One of the disadvantages of using the LC-SLM is the limited corrective range and the dispersion in the birefringence. Phase wrapping seriously degrades the Strehl Ratio. Currently, the Hamamatsu LC-SLM is a commercially available product having very high resolution.

The MEMS mirror is 3.3 mm square and has 144 actuators. We expect to have this mirror working in closed loop in our test bed by August 2001.

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The MEMS device has lower resolution than the LC-SLM but does not suffer from any dispersion or phase wrapping issues. The main limitation is its’ small stroke.

In Year 3, The University of California at Berkeley and Lucent Technologies have been funded by CfAO to fabricate MEMS mirrors with strokes of 12 µm or greater. This collaboration promises to yield the first devices with specifications well matched to vision science needs for high stroke.

**2.1.12 Potential Ophthalmic Instruments for Vision Science**

CfAO has identified at least six ophthalmic instruments that might benefit from the incorporation of adaptive optics and will build prototypes of several of these devices. The prototypes will be inserted in clinical environments where their clinical utility can be evaluated. Once clinical utility has been established, corporate partners will be identified, and a commercialization plan developed and implemented. Potential AO-equipped ophthalmic instruments include:

1. **Phoropter/Autorefractor** (discussed above)
2. **Surgical Microscope or Slit lamp.** Both of these devices could benefit from adaptive optics to increase the resolution available for diagnosis and delicate surgical procedures. We are engaged in discussions with Gene De Juan, Mark Hamayun, and Vas Sadda (retinal surgeons now at Willmer Eye Institute but soon to move to the...
Doheny Eye Institute) to understand how to best meet the surgeon’s needs with this instrument.

3. **High Resolution Photocoagulator.** High energy laser radiation is often focused on the retina to destroy cancerous tissue, to spot weld a detached retina back in place, or to prevent bleeding from the retinal vasculature as in diabetic retinopathy. Unfortunately, this beam also destroys vision locally. The use of adaptive optics may allow the delivery to the retina of a more tightly focused beam that would reduce damage to healthy tissue relative to current photocoagulating methods.

4. **Flood-Illuminating Fundus Camera.** Based on the design of the Rochester 2\textsuperscript{nd} generation adaptive optics system for the eye, this instrument uses a flash lamp to flood illuminate the retina, at which point high resolution retinal images can be acquired through adaptive optics. The principle advantages of this device are that it has high transverse resolution and it will provide accurate radiometry of retinal structures.

5. **Confocal Scanning Laser Ophthalmoscope.** Based on the fundus camera under development at the University of Houston, this device combines confocal imaging and adaptive optics to optically section the retina at high transverse and axial resolution.

6. **Coherence-Gated Fundus Camera.** This device will be based on the fundus camera under development at Indiana University. The incorporation of coherence gating, like confocal imaging, will allow this device to optically section the retina at high transverse and axial resolution.

### 2.1.13 Additional Year 3 Plans for Collaboration between Astronomy and Vision Science

**Image Processing for AO-equipped Fundus Cameras (UC Santa Cruz, Rochester, Houston).** We plan to apply deconvolution techniques to retinal images obtained with adaptive optics systems. For Year 3, this includes development and application of both multi-frame blind deconvolution and deconvolution from wavefront sensing with the scientific goal of improved cone segregation.

Performance Analysis of Rochester AO system. LLNL and Rochester will collaborate on improving methods of quantifying system performance in vision AO systems.

**Literature Cited**


### 2.2 Goal 1 – Astronomical Science, Personnel and Research Narrative

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Narrative: Goal 1 - Astronomical Science

The CfAO is currently supporting a number of astronomical science projects that were chosen because they both advance the development of AO and provide synergistic interactions within the Center. Benefits of these programs to the Center include the production of useful observational and analysis tools (see Goal 2) and input into the Center's education and outreach activities. In the first two years, this goal was divided into three meta-projects related to different aspects of current AO systems' performance. Highlights of the work carried out in Year 2, during which the focus has shifted from imaging alone to an inclusion of spectroscopy, are provided below. In addition to research, CfAO members organized a special topics session at the 9 January 2001 meeting of the American Astronomical Society on "Science with Adaptive Optics" (Co-organized by Ghez and Macintosh), the intent being to highlight progress in astronomical science using all the major AO systems. This included invited talks from members both inside and outside the CfAO.

2.2.1 High Contrast Imaging: Protoplanetary disks and low-mass companions to stars

A component of CfAO's astronomical research is searches for protoplanetary disks and low-mass companions to stars; a collaboration between UCLA, Caltech, and LLNL. The faint companion and disk work is driven by the goal of achieving high-contrast imaging and astronomically by the need to find answers to the following two questions:

1. What is the distinction between the formation of stellar companions and the planetary mass companions?
2. What are the critical roles disks play in the origin and evolution of stars and planets?

In Year 1, we reported a number of intriguing low-mass companions, ranging from the brown dwarf regime to the young (~2-10 MYr) planetary mass regime. In Year 2, the focus has been to perform a systematic characterization of the imaging performance of various AO systems designed for high dynamic range (at Lick, Palomar, and Keck). The long-term goal is to optimize those systems that are optimized. Figure 2-14 shows the characterization of the Keck AO system (using the interim KCam test camera) in contrast to Hubble Space Telescope's NICMOS coronographic system. The comparison is based on a survey of young stars in the nearby association of TW Hydra. We are carrying out similar work is being carried out at Palomar and Lick on stars with planetary companions.

![Figure 2-14](image-url)
(discovered in radial velocity surveys) and nearby M-dwarfs.

### 2.2.2 Extragalactic Adaptive Optics

The prime goal here is to use AO to study the morphology, metallicity and star formation rates of faint galaxies as a function of age in the early Universe, thereby determining when and how galaxies such as our own Milky Way, formed. This work is a collaboration between UCSC, UCLA, and UCSD. This program is underway on both the Keck and Gemini AO systems and has resulted in a new collaboration between UCLA and UCSC. In Year 1, the feasibility of obtaining AO images of faint galaxies, such as the one shown in Figure 2-15 was demonstrated.

Year 2's activities have focused on improving the analysis routines to determine not only

*Figure 2-15*: In a collaborative project between UCLA and UCSC teams studying distant galaxies, the Keck AO system was used to obtain near-infrared images of what may be the most distant field galaxy imaged with adaptive optics (AO). Shown is a false color image combining HST V, I and the resampled Keck AO observations. Regions with intense star formation appear blue. N is to the top and E towards the left, while older stellar populations have a yellowish color. Courtesy, D. Koo, UCSC

*Figure 2-16* Comparison of observed $z\sim0.5$ galaxies and models of evolved local samples are made here via contours of the probability of given values of evolution being consistent to within the uncertainties of our measurements; no evolution is the upper left corner. The observed sample is systematically smaller and brighter than a no-evolution model allows. Courtesy J. Larkin, UCLA.

the size and brightness of the bulge and disk, but also their reliability, since a lack of understanding and reliable modeling of AO point spread functions has plagued many AO science programs. This year has also resulted in the first statistically significant sample of faint distant galaxies observed with AO, allowing detailed comparisons between this sample (at $z\sim0.5$) and local samples of galaxies (see Figure 2-16). The observed smaller, brighter disks at redshift of 0.5 (~5 Billion years ago) are consistent with theories that most galactic disks were in place significantly earlier (probably by $z\sim1$) and have continued to grow by modest accretion of new material.
2.2.3 Crowded Field Imaging and Spectroscopy - Stellar Clusters

Studying the Center of our Galaxy addresses several technical, educational, and astronomical issues associated with Adaptive Optics. Technically, the Galactic Center presents many challenges, including working with dim, off-axis guide stars, and with crowded stellar fields at near-infrared wavelengths. This program uses a variety of different systems (Keck vs. Gemini; and in the future Natural Guide Star (NGS) vs. Laser Guide Star (LGS)) to examine the impact of Adaptive Optics. The specific parameters being studied are (1) PSF quality (overall Strehl), stability and anisoplanatism and (2) photometric, astrometric, and spectroscopic accuracies that can be achieved in such a crowded stellar field. As these results are applicable to a number of different studies, they are of large interest to the general CfAO community. Educationally, this program offers tremendous opportunities both to display the power of AO and educate the general community. The benefits of AO are visually clear and the subject of the supermassive black holes at the center of our Galaxy is of great interest for the public. Since much of the astronomical investigation rests on basic principles of physics, it also provides a useful tool for educating the public through lectures, documentaries, and text books. Astronomically, studies of the environment of the Galaxy's central supermassive black hole provides the means to measure the dynamics, distribution, and properties of the stars in the central stellar cluster.

While Year 1's activities were focused on “imaging” data from Keck and Gemini, in Year 2 this was expanded to include the challenge of obtaining the first spectroscopic observations of the central 1 arcsec$^2$. This provided data to determine the spectral types and radial velocities for the stars located in this critical region (see Figures 2-18).

![Figure 2-17: Images of the central 1 arcsec$^2$ from the slit-viewing camera on NIRSPEC+AO at Keck show the position of the slit during three separate nights. Courtesy, A. Ghez, UCLA](image1)

![Figure 2-18: The resulting spectra, which contain the K=14-15 stars shown above as well as the brighter (K=10) IRS 16 NW, a well-known helium emission-line star. None of the fainter stars show CO absorption, indicating that these are all likely to be young, early-type main-sequence stars. This raises many interesting questions regarding how these stars could have formed so recently in the proximity of a supermassive black hole. Courtesy, A. Ghez, UCLA.](image2)
2.2.4 Extended Object - Solar System
The scientific goal of this program is to study outer solar system objects that retain information regarding conditions in the early solar system. This is a collaboration between UC Berkeley, Caltech, and LLNL. In Year 2, images and spectra were obtained for Titan, Neptune, Uranus, and Io. A major effort was expended on testing and comparing several deconvolution methods (MISTRAL, IDAC, Lucy-Richardson) to enhance the sharpness of the images and correct for aberrations caused by the use of extended reference sources.

We have demonstrated the power of spectroscopic AO measurements on a number of extended planetary objects. Figure 2-20 shows an example of spatially-resolved infrared spectral measurements of Saturn's moon, Titan, which reveal the presence of tropospheric clouds at the South Pole of Titan. Because atmospheric methane in Titan's atmosphere acts as an altitude discriminant, the discovery of high geometric albedo at the tropospheric altitude (central image of the three) suggests methane condensate. This discovery was possible through the integrated coordination of planetary scientists and AO instrument builders.

Figure 2-19 A deconvolved Keck AO/NIRSPEC image of Uranus from a data set that had a double peaked PSF. Although the bright, outer Epsilon ring has been routinely seen, this is the first ground-based detection of the faint inner rings. The disk has been artificially darkened by a factor of 20 to show the rings and planet on the same images. Based on this successful reconstruction, the near-infrared albedoes of particles in the individual ringlets were extracted, a feat not possible with Hubble Space Telescope data. Courtesy, I. de Pater, UCB.
### 2.3 Goal 2 – Bringing AO to the Community

**GOAL 2: BRING AO TO THE COMMUNITY**

**PI Name:** Andreas Quirrenbach

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Narrative - Goal 2: Bringing AO to the Broad Community

This CfAO Goal has two components: 1) sponsoring Summer Schools and workshops that familiarize a broad community of astronomers and vision scientists with the tools of adaptive optics; and 2) developing and disseminating methods and software tools for the quantitative analysis of adaptive optics images in both astronomy and vision science.

2.3.1 CfAO Summer Schools and Workshops

2.3.1.1 Annual Summer School

The CfAO holds an annual week-long summer school on adaptive optics, in Santa Cruz CA. The target audience is graduate students and postdocs, but senior researchers are also welcome to attend. Emphasis is given to topics that are of interest to astronomers and vision scientists alike.

The first summer school was held in July 2000, and provided a thorough introduction to adaptive optics for non-experts. During Year 2 we prepared text versions of these introductory lectures, which will be published as a book by the Astronomical Society of the Pacific. The first summer school was attended by 100 participants.

The second summer school (August 2001) is covering advanced topics such as image processing, mathematical tools for AO, MEMS deformable mirrors, tomographic wavefront sensing, and computer simulations of AO systems. Approximately 100 registrations have been received for the second summer school. In the future we intend to hold “introductory” and “advanced” schools in alternate years. Many of the topical presentations at the 2001 summer school will be given by CfAO graduate students and postdocs. Based on feedback from the first summer school, we will also conduct hands-on computer classes to give attendees “real-life” experiences in confronting and reducing adaptive optics data.

2.3.1.2 Workshops

The CfAO sponsors 15 to 20 workshops each year. These range from large formal sessions at international meetings to smaller special-topics discussions, and are described in detail in Section 8.3 of this Report. Highlights in Year 2 include the following workshops:

A CfAO-sponsored workshop entitled "Calibration of Wavefront Sensors for the Human Eye,” part of the 2nd International Congress on Wavefront Sensing and Aberration-Free Refractive Correction. The workshop was attended by 136 vision scientists, refractive eye surgeons, and commercial manufacturers.

A workshop on Extremely High Contrast Adaptive Optics (March 2001) which helped to set the direction for our new “Extreme Adaptive Optics” theme area.

2.3.2 Tools for the Quantitative Analysis of Adaptive Optics Data

Tools for analysis of AO data are important for several crucial reasons. Adaptive optics provides images with unprecedented resolution. But the quantitative interpretation of these images is sometimes hampered by artifacts, due to incomplete correction of wavefront errors. Several groups within the CfAO are working on a better understanding of the exact nature of these artifacts in applications of AO to astronomy and vision science. We are developing algorithms and software tools to restore the full information content in such images. We have made these tools and associated test data sets publicly available on the CfAO web site.

Our current efforts are aimed at answering the following questions: How can the point spread function (or PSF, i.e. the image of a point source as observed with the AO system) be measured? How does it vary with time, and across the full angular field of an image? What is the most efficient parameterization of these effects, and which algorithms can be used to remove them? What additional calibration data have to be taken during the observations? What are the limitations on high-contrast imaging imposed by incomplete knowledge of the PSF? Can methods being developed for astronomy also be used to improve the results from AO techniques in vision science?

2.3.2.1 Blind Deconvolution: A New Tool to Determine the Point Spread Function in Images from AO Systems

The traditional way of determining the point spread function (PSF) in astronomical AO imaging is to alternate between the object of interest and a nearby star, and to use the image of the star as a proxy for the true PSF in the observations of the astronomical target. This approach suffers from a number of shortcomings. Most notably, the atmospheric turbulence or “seeing” changes on time scales shorter than the switching cycle between the target and PSF calibrator star, which leads to systematic errors and artifacts. Additional problems can arise from the fact that the correction of the AO system depends on the brightness and color of the reference star, and therefore will be slightly different for the target and calibrator observations. Finally, the observing efficiency “on target” is greatly reduced by the need to observe calibrators frequently. Consequently, we are developing methods to measure the PSF more reliably and with less “observational” cost.

Blind deconvolution is an advanced image-processing technique that permits determination of point spread functions (PSFs) internal to a given data set, by comparing multiple exposures of the same object. In Year 2 we used this method to analyze images of the ring around Uranus taken with the Keck AO system. This study is one of very few so far to use blind deconvolution to derive hard scientific results, and it is by far the most challenging. (Previous work involved simple sources such as binary stars and Jupiter’s moon Io, which have high-frequency PSF information easily available in the image itself.) By contrast, Uranus is a very large source (4 arc sec in diameter); closing the AO loop on it introduced highly visible systematic errors in the PSF. These were analyzed and successfully removed using blind deconvolution applied to four separate data subsets taken at multiple camera rotation angles. The resultant image shows a single ring around Uranus that varies in...
brightness smoothly as a function of azimuth. See Figure 2-19. The brightness variation contains important information about the number density and composition of ring particles. This is a collaboration between UCSC, UC Berkeley, and LLNL.

In a second study, blind deconvolution was used to analyze images of the Galactic Center taken with the Gemini Telescope’s Hokupa’a AO system. This was another novel application of blind deconvolution - in this case to a very crowded star field. Blind deconvolution is crucial in these situations, because normal techniques for analyzing stellar fields rely on finding the PSF from isolated bright stars. Here this was not feasible because of extreme crowding and because the AO PSF is varying over the field and must be determined on a dense grid. However by breaking the image into small sub-regions each containing many stars, we found that blind deconvolution could determine the local PSF in each sub-region separately using all data on both bright and faint stars simultaneously. The method also provides a catalog of all objects in the frame in a single pass, with no need to laboriously clear out layers of bright stars to find fainter ones, as is required with other techniques. Most of the objects in the Galactic Center image turned out to be stars (as expected), but a handful appear to be resolved and potentially are very interesting astronomical sources. These pilot studies pave the way towards a broader use of the IDAC blind deconvolution code available on the CfAO Software Website.

2.3.2.2 Characterization of Anisoplanatism
A crucial issue for the reduction and interpretation of astronomical AO data is anisoplanatism: objects on the optical axis of the telescope are seen through different atmospheric turbulence than objects that are off-axis. This leads to a variation of the PSF with position in the field. Highest performance of the AO system can only be achieved for stars near the optical axis; images of other objects are more blurred, the farther they are separated from the guide star. This effect can be seen in Figure 2-21, an image of the Orion Trapezium star cluster. The guide star is the bright star above and to the left of the center. This star is well corrected by the AO system: it has a sharp peak and parts of diffraction rings are visible around it. The stars in the lower right corner, however, have much broader peaks that are not circular, but are distorted towards the guide star. This year we assembled a data base of images from several AO systems that are suitable for quantitative modeling of the spatially varying PSF. We have shown that in many cases a convolution of the on-axis PSF with an elliptical Gaussian (whose parameters depend in a predictable way on the distance and position angle from the guide star) appears to provide a good description of the PSF variation.

In related work, we conducted a new concerted empirical study of astronomical anisoplanatism with the Lick Observatory natural-guide star AO system. We imaged the globular cluster M15 continuously in three colors over an 8-hour period on successive nights. These data are yielding a comprehensive characterization of anisoplanatism as a function of color, airmass, and time. This work is a collaboration between UCSD, UCSC and a visiting faculty member from the University of Maryland.
Figure 2-21: Image of the Orion Trapezium cluster obtained with Adaptive Optics. The field of view is approximately 70 x 70 arc seconds. The enlarged section in the upper left corner shows the guide star. The other two enlargements show stars far away from the guide star. The guide star’s PSF has a sharp peak, while the PSFs of the other stars are more blurred and are elongated in the direction towards the guide star.

2.3.2.3 AO Data Reduction with Spatially Varying Point Spread Function

Once we know how to describe the variation of the point spread function with position in the field, how do we determine the relevant parameters and use them in the quantitative analysis of AO images? This is largely uncharted territory, and new algorithms need to be developed. The simplest case is doing photometry in a field of point sources, a situation that arises frequently in astronomy. To measure the positions and individual brightness of the stars, one fits copies of the PSF to the peaks seen in the image. Figure 2-22 shows the result of a fit with a constant PSF, carried out using the StarFinder computer code. The PSF was extracted from the image itself, using seven bright stars that do not have a companion star nearby. Since the resulting PSF is approximately circular, the only way for the computer code to obtain a reasonable fit to the elongated image of stars far away from the center is to assume that they consist in fact of several stars, and to use several copies of the PSF to fit one elongated peak. However, we know that these are single stars, so most of the stars found by the program are false detections. Furthermore, it is not clear how to obtain the correct position and flux of the real stars.

In order to overcome these problems, we modified StarFinder to use a spatially varying PSF. This is done by convolving the on-axis PSF with an elliptical Gaussian. The width of this Gaussian in the radial and azimuthal direction is proportional to the distance from the guide star. Figure 2-23 shows the result of this algorithm applied to the image of the Trapezium cluster. Now the objects in the corners are indeed detected as single stars.
Figure 2-22: Same image as Figure 2-21. Here the green circles mark the stars identified by the StarFinder program when a constant and circular PSF is assumed. To fit the elongated objects far away from the guide star, the computer code uses several copies of the PSF and (falsely) concludes that each is a multiple-star. Since the stars are in fact single, most of these are false detections.

A crucial step in this analysis is determining the relation between the width of the Gaussian and the distance to the guide star. Until now this has been done “by hand”, based on measurements on the image of the Trapezium. We are now extending StarFinder to automatically determine the broadening of the PSF as a function of the distance to the guide star.
Figure 2-23. Same as Figure 2-22, but using spatially varying PSF. For each peak in the image, a PSF is used that was broadened according to the PSF degradation at this position in the image. Therefore, the program detects that the elongated objects are images of single stars and correctly fits them as single sources.

2.3.2.4 Atmospheric Characterization from AO Telemetry Data
Data collected by the wavefront sensor in an AO system provide a wealth of information on the state and evolution of the atmospheric turbulence. As most current AO systems make little use of this information, we have initiated a project on atmospheric characterization using telemetry data from the Keck adaptive optics (AO) system. An objective of this work is to develop a tool for extracting atmospheric turbulence parameters automatically whenever the AO system is running. We will then determine whether a feedback of these parameters into the AO system’s control law, and adjustment of system parameters such as the wavefront sensor frame rate, will lead to improved AO performance. Another goal is to establish a data base of atmospheric turbulence conditions above the Keck telescopes. To date we focused on understanding the system, on calibration of the necessary data, and on developing a tool that performs the required operations. In the near future we will undertake acquisition of a data base of atmospheric conditions at the Mauna Kea summit, and investigations concerning the above-mentioned
feedback loop. Application of this project to the Mount Palomar AO system has also been started and will produce first results shortly. This is a collaboration between UC Irvine, Caltech, and the Keck Observatory

2.3.2.5 Limitations of High-Contrast Imaging
Many important astrophysical questions require observations of very faint objects in the immediate vicinity of much brighter stars. The development of optimized observing techniques for high-contrast science is therefore an important aspect of our work. In many AO systems, the majority of wavefront errors that lead to detrimental artifacts of the PSF appear to arise at the perimeter of the telescope pupil. Hence there may be significant scientific advantage to stopping down the pupil slightly. We have executed an experiment with the AO system at Palomar Mountain using both 5% and 20% undersized diameter Lyot stops within the PALAO system’s science camera, the Palomar High Angular Resolution Observer (PHARO). Preliminary results show that the Strehl ratio was increased and the Strehl stability, in particular, was significantly improved (see Figure 2-24). Quantification of these results may provide new experimental approaches for adaptive optics observers throughout the AO community.

2.3.2.6 CfAO Software Website
The new data reduction algorithms and tools described above are publicly available on the CfAO Software Website. This site also provides users with additional software for adaptive optics, and will soon be a source for carefully screened publicly available adaptive optics test data. The CfAO Software Website at the University of California,
San Diego can be accessed through http://babcock.ucsd.edu/cfao_ucsd/software.html or by following links from the main CfAO website (http://cfao.ucolick.org).

Although many researchers invest a great deal of effort in writing software to solve research problems, few of their software packages are distributed to the general community. Further, as researchers change jobs and research interests, the software they write is often left behind and not used to its full potential. Re-use of software, especially in very technical areas like adaptive optics, improves efficiency and allows the community to improve algorithms by working with existing, publicly available programs. The CfAO Software Website enables researchers to contribute software packages, with the knowledge that they will be tested and made available to the community. Some researchers choose to run their own websites, and in those cases the CfAO Software Website simply links to the appropriate web pages. To the AO community user, the CfAO Software Website provides a one-stop source for adaptive optics related software. As of July 2001, the software contributions consist of seven packages:

1. **A++**. This complex package originally written by Walter Wild has been modernized by the U. of Chicago AO group and has an extensive user manual. A++ calculates the reconstructor matrix for an AO control system, which is used to compute deformable mirror commands from wavefront sensor data. Most astronomical Shack-Hartman type AO systems currently in operation use versions of the reconstructor matrix calculated by A++.

2. **AO Simulation Package**. This software written by François Rigaut (Gemini Observatory) simulates an AO system. The user sets the parameters of the AO system and telescope. The software calculates the closed loop performance of the telescope and AO system and simulates the observation of a star using a phase screen model for turbulence in the Earth’s atmosphere.

3. **AOTOOLS**. This set of scripts written by Eric Steinbring (UCSC) simplifies the reduction of near-infrared astronomical data acquired with an AO system. Most astronomical AO data today are acquired at near-infrared wavelengths.

4. **idac**. This is a large package of software for AO data reduction using blind deconvolution. The software was written and documented by S. Jefféries, J. Christou (UCSC), K. Hege, and M. Cheselka. Blind deconvolution is a technique that allows the PSF to be determined by analysis of multiple images of a single science field, which may or may not contain point source(s). Blind deconvolution has the advantage that separate telescope pointings to acquire observations of a calibration point source for PSF estimation are not required.

5. **Rainer’s Binary/Speckle Package**. This software package was written by Rainer Köhler (UCSD) to reduce speckle imaging data on binary stars. Speckle imaging methods take advantage of short exposures to “freeze” the atmospheric turbulence. The binary information is preserved in “speckles”, or small bright regions. The total image consists of a large number of speckles and considerable
analysis must be done to extract scientifically useful measurements from the raw image. The package is also useful for AO observations of binary stars.

6. StarFinder. This software package is used to reduce AO data in crowded stellar fields. Bright stars are used initially to estimate the PSF. The PSF and detection of faint stars are iteratively improved until the entire field has been analyzed. StarFinder, written by Emiliano Diolaiti and colleagues at Bologna Observatory, carries out some of the fundamental tasks in the analysis of AO data. It provides both PSF estimation and, by using the PSF, astrometry and photometry in crowded fields.

7. Theo ten Brummelaar’s Strehl Code. This software is used to analyze an AO observation of a point source to estimate the Strehl ratio achieved. The Strehl ratio is the ratio of the peak intensity actually observed to the peak intensity that would be observed if the telescope were operating at the diffraction limit. The Strehl ratio is the most common figure of merit for an AO system.

The website also includes two papers, “Adaptive Optics with Laser Guide Stars: Basic Concepts and Limitations,” by A. Quirrenbach and “Reduction of the Gemini Science Demonstration Data of the Galactic Center,” by R. Köhler. We plan to expand this section of the CfAO web site so that it will provide a repository of introductory articles and useful tips for all new users of AO systems.

We are in the process of making available on the web a large set of AO test data that can be used to evaluate and cross-compare data reduction algorithms. Making these data available with proper documentation will be a service to the broad AO community. These AO data complement the software, since they allow software packages to be compared using common data sets.

2.3.2.7 Image Processing for Vision Science

While image processing and deconvolution are routinely used to analyze astronomical AO data, relatively little attention has been paid to application of these methods in vision science AO. We have therefore started a program to apply blind deconvolution methods to AO retinal imaging.

A current aim of vision research involves identifying individual cones in the retina, and determining whether they respond to red, green, or blue light. These cone types reveal themselves through different intensities in retinal images taken in different colors. However contrast is currently marginal, the time to measure is long, and the needed light levels are uncomfortably high. Blind deconvolution will sharpen the effective resolution of the images, and will speed up the process of identifying the various cone types. This is probably the first application of advanced image-processing techniques to vision science adaptive optics, and represents one of the unique new collaborations between vision scientists and astronomers made possible by the CfAO. This is a collaboration between UC Santa Cruz Astronomers and the University of Houston, vision scientists.
2.4 Goal 3 – Development of Advanced Instruments for AO

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2.4 Narrative

Goal 3 concentrates on developing instruments and technologies that produce a scientific product from a highly corrected adaptive optics beam. Due to the extremely high angular resolution and additional complexities of adaptive optics, many traditional technologies for constructing cameras and spectrographs are not appropriate or need significant modification. Adaptive optics also presents new opportunities to the instrument developer including three dimensional sectioning of the retina, compact high spectral resolution spectrographs and high throughput high resolution spectrographs. The four projects within this goal (two for vision and two for astronomy) try to address some of these unique challenges and opportunities and develop both working instruments, but also technologies that other researchers can use.

The two vision science instruments both attempt to explore a new area in high resolution imaging of the living retina: three dimensional sectioning. The two groups from the University of Houston and Indiana University are working closely to develop two different techniques for producing sequential sections. Houston’s work on a scanning laser ophthalmoscope is the most straightforward approach and should produce the first images by the end of Year-2. The Houston group has already commenced initial use of their system both with model eyes, and with living subjects. With a new laser installed in
June, they should start achieving good corrections soon. Indiana is using a coherence gated camera (based on a Michelson interferometer) to achieve better contrast and finer sectioning of the retina and does not require scanning a beam across the eye. Both instruments require significant interaction with the AO system and have been developed in close cooperation with the University of Rochester. The latter are building the next generation AO system for vision science. These instruments are described in detail in Sections 2.1.6 and 2.1.8.

The two astronomical science instruments are pursuing spectrographic techniques behind an AO system, as well as high contrast imaging. For astronomy, AO provides high angular resolution, but only over a small field (< 60 arcseconds) and with a variable and irregularly shaped point spread function. The beam sizes are also close to an order of magnitude smaller than in non-AO instruments.

In the IRCAL instrument being developed by U.C. Berkeley, a smaller beam size is being used to make a very capable compact instrument. Compactness is important, as the instrument must mount on the adaptive optics bench and ride with a changing gravity vector on a large telescope. To achieve high spectral resolution with such a small beam the Berkeley group is collaborating with LLNL to use high index of refraction gratings etched from silicon. They have now achieved first light on an astronomical target with the silicon grisms at the Lick AO system. The Berkeley group has also been developing coronagraphic masks for IRCAL and is improving the user interface of the instrument to make the complexities of an AO instrument more manageable by astronomers. This team works closely with the U.C. Observatories and LLNL to match the instrument to the AO system and the user community.

UCLA is designing the next generation of AO science instrument. Because of the small, but complex nature of most AO science targets and the very large detectors now available, this group has concentrated on building spectrographs that can simultaneously take spectra over a contiguous rectangular region; a so called integral field spectrograph. Similar to the vision science instruments, the integral field spectrograph takes three dimensional data, but the third dimension is wavelength instead of depth within the eye. The UCLA group has used CfAO funds to build a working prototype of this instrument as well as to develop a full design of a facility class instrument for the Keck AO system. This instrument design is mature enough to have received funding through a preliminary design review from the Keck Observatory and will not require CfAO funds for Year 3. This team is also working with Caltech to design an advanced multi-object integral field spectrograph for a multi-conjugate AO system on a 30-meter telescope. Its development is being coordinated with the CELT telescope and AO teams at UCSC and JPL.

Principal Investigators and research groups within Goal 3 and have been active in education and public outreach. This has included public lectures, presentations to professional organizations like the American Astronomical Society and the International Congress on Wavefront Sensing and Aberration-free Refractive Correction. It also includes participation in the COSMOS program, CfAO summer school and Chautauqua meetings. The University of Houston College of Optometry has also made a large number
of very popular rubber eyes that illustrate how the eye works optically and has distributed them to the COSMOS summer school.

2.4.1 Optimizing Adaptive Optics with Applications to OCT Imaging of the Human Retina
This research has been described in Section 2.1.8. Under the Year 1 and Year 2 Goals it has previously been reported under Goal 3. However under the new Themes it will be part of the theme “Compact Vision Science Instrumentation for Clinical and Scientific Use”.

2.4.2 An Integral Field Spectrograph Optimized for AO
The UCLA infrared laboratory (Larkin) is currently designing an integral field infrared spectrograph (IFS) for the Keck AO system. The goal of the current instrument design is to produce spectral data cubes with near diffraction limited spatial resolution. Very faint imaging and low-resolution spectroscopy can be achieved through spectral binning and software suppression of atmospheric emission lines of OH. We believe that NSF Center funding is crucial in optimizing the instrument’s performance and in helping to secure primary construction costs. The team is also developing general-purpose data reduction and analysis software that will be made available for other integral field instruments. The long term plans include investigating new instrument concepts built around advanced AO systems.

To date the team has concentrated on developing the current instrument design to the level of preliminary design review. This review occurred June 28-29, 2001. The PDR document itself is a 280 page presentation of all aspects of this $4 million instrument. A critical design review is scheduled for January 2002.

Figure 2-25. This is a rendering of the integral field spectrograph’s optical benches and mounting structures as conceived for the preliminary design review in June, 2001. Not shown is the very small lenslet array that is at the heart of the instrument. It breaks up a rectangular field of view and allows for each piece to be dispersed independently. The final data product has 1024 individual spectra with 1600 spectral channels each.
Integral field spectrographs intrinsically produce “intense” data products. The team developed two algorithms for deblending and extracting these data products and producing cubes of data (x,y,wavelength). The best algorithm was developed after discussions with other Center members and is based on wavefront reconstruction techniques. The success of this cross cutting application was unexpected and is a very gratifying result of working in “Center mode”. The team has demonstrated that an iterative algorithm can accomplish the OSIRIS data reduction problem in a reasonable amount of time and with very good accuracy.

The UCLA team has also been working on the CELT instrument working group to define new instrument concepts for the CELT 30-m telescope. This work has become more concrete during Year 2. Caltech is collaborating with UCLA to develop several instrument concepts for adaptive optics integral field spectrographs. They are experimenting with the scattered and diffracted light properties of lenslet arrays in the infrared and are using this information to design a fiber fed instrument. A quote has been received for a fiber bundle and infrared testing should begin before the end of Year 2.

2.4.3 An Adaptive Optics Scanning Laser Ophthalmoscope
This research will in the future also be part of theme “Compact Vision Science Instrumentation for Clinical and Scientific Use”. It is reported in detail in Section 2.1.6

2.4.4 IRCAL Camera and Spectrograph for the Lick Laser Guide Star AO System
Through a program (Graham) of continued improvement and upgrades, IRCAL has become the de facto imager and spectrometer for the LLNL AO system at the Lick 3-meter telescope. This instrument was scheduled for 27 nights of use from December 2000 to July 2001. The upgrades have focused on the implementation of spectroscopy and on increased efficiency by making it easier to use with better control and display software.

An efficient way to implement low-cost spectroscopy is to convert a camera into a spectrometer by locating a grating/prism hybrid, known as a grism, in the instrument’s pupil plane. Most grism materials have low refractive indices (n~1-2) which severely limits the grism geometry. Moreover, classical fabrication techniques limit the groove density to >30 mm$^{-1}$. This limits the order of interference. The net result is that grism spectrometers rarely achieve spectral resolutions R>300. Micro-fabrication using Si offers the advantage of working with a high index material (n=3.4 at 2.2 microns) which can be ruled coarsely.

The notion of fabricating blazed gratings in Si is based on the idea that certain etchants (e.g., KOH) attack different crystal planes of Si at different rates. Accurate and ultra-smooth groove facets can be obtained especially for infrared gratings and shallow groove grisms. This has been known for some time, and small gratings (~1 cm$^2$) were etched by Tsand & Wand. The first LLNL grating was fabricated in 1994. However, this grating had large scatter due to random defects in the Si substrate, grating ghosts due to periodic errors in the photolithography mask, and several waves of wavefront distortion due to an over-etch problem. Substantial progress has been made to understand and reduce the
sources of scatter and wavefront error in etched Si gratings. We have used defect etching to verify that the substrates are of high quality and that they can be polished to the required optical flatness without producing subsurface damage. The effect of different etch mask materials and etching variables on scatter and wavefront aberration of test gratings have been compared. Gratings masked with silicon nitride achieved sufficiently low wavefront distortion to be useful in high resolution spectroscopy. The scatter was improved by a factor of two.

An interferometric method now exists which eliminates grating ghosts. Another source of scattering occurs when the etch mask is misaligned with the crystal plane so that the resultant grooves suffer dislocations. By procuring precision aligned and polished Si substrates this has been eliminated. The combination of these approaches has reduced overall wavefront error by a factor of three to <80 nm rms. Our proposed goal of reducing the total scattering loss to <5%, i.e., comparable to the level found in a classically ruled grating, has almost been met.

Observations with IRCAL and the LLNL natural guide star system have been used to measure and demonstrate the optical performance of the second generation of silicon grisms made at LLNL. K-band spectra of a total of six T Tauri and Ae/Be stars and their close companions were obtained at a spectral resolution of 2000. These results represent the first scientific observations conducted by the high-resolution silicon grisms. A spatial resolution of 0.15 arcsec was achieved to allow observations of the companions with separations between 0.3-1.3 arcsec. Observations of T Tauri N and S show the well known result that T Tauri S is much redder. But based on very weak CO absorption bands in the IRCAL spectra, both stars have the same spectral type indicating the major difference is actually due to the presence of dust. The profile of the Brackett gamma emission line is broader in T Tauri N and shows a P Cygni signature possibly indicating the presence of an outflow.

This project is a collaboration between UC Berkeley, LLNL, UC Santa Cruz, and Pennsylvania State University.
### GOAL 4 - ADVANCED AO TECHNOLOGY

**PI Name - Claire Max**

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Narrative Goal 4 - Advanced Adaptive Optics Technology
The fourth goal of the CfAO is to pursue advanced technologies that will make the next generation of AO systems more powerful, more versatile, and/or less expensive. Key technologies include compact spatial light modulators that correct optical distortions for the human eye and for large astronomical telescopes; powerful lasers that make artificial stellar beacons for astronomy; and adaptive optics concepts for the next generation of giant telescopes. The most important deliverables will be: MEMS (Micro Electro Mechanical) deformable mirrors of high optical quality, for both vision science and astronomy; compact and efficient lasers for laser beacons; and the design of adaptive optics systems for extremely large telescopes.

2.5.1 Advanced technologies for wavefront control and correction
Compact, reliable, and low-cost wavefront control and correction are needed to correct high-order aberrations in the human eye, and for astronomical adaptive optics systems that produce very high wavefront fidelity (for example to image faint planets around bright stars). The CfAO is spearheading adaptive optics applications of silicon Micro Electro Mechanical (MEMS) deformable mirrors. In addition the CfAO is testing liquid crystal spatial light modulators for wavefront correction, and next-generation infrared detectors for wavefront measurement. To fully evaluate and integrate these components, the CfAO is developing laboratory test-beds to be used for systems integration and testing within closed-loop adaptive optics systems.

2.5.1.1 MEMS Deformable Mirrors
Together with industrial and academic partners, the CfAO has developed a strategy to design and produce high-optical-quality MEMS deformable mirrors for use in vision science and in astronomy. This is a highly coordinated activity within the Center, with strong participation from UC Berkeley, the University of Rochester, Lucent Technologies, Lawrence Livermore National Laboratory (LLNL), Boston University, Boston Micromachines Corp., Sandia National Laboratory, and the Air Force Research Laboratory (AFRL). The CfAO MEMS development plan is heavily leveraged from existing programs at participating partner and collaborator institutions.

In Year 1 the Center drew up a comprehensive set of requirements for the next generation of MEMS deformable mirrors, based on the specific needs of both vision science and astronomy. Many of the technologies (e.g. fabrication methods for high optical quality, development of optical coatings, and packaging technologies) are common between these two applications. However vision science applications typically need higher stroke and fewer degrees of freedom than the astronomical applications of MEMS.

We commenced Year 2 with a MEMS workshop bringing together researchers from the CfAO institutions involved in MEMS development, with those researchers from industry, aerospace, and academia who were knowledgeable in MEMS and their applications in vision science and astronomy. The following institutions were represented - VISX, JPL, Goddard Space Flight Center, and the University of Minnesota. Our workshops have been very helpful in focusing our MEMS investments on specific technological advances needed for vision science and astronomy.
The CfAO’s MEMS development plan for Year 2 included three risk-reduction strategies: 1) Parallel development paths based on device designs generated at Boston University (BU) and the Air Force Research Laboratory (AFRL); 2) implementation at two MEMS foundries (Cronos Integrated Microsystems and Sandia National Laboratory); 3) having packaging and drive electronics provided by two institutions (Lucent, based on their intensive investments in this area for optical cross-connect switching, and Boston Micromachines Corporation, working with BU). The development path based on the AFRL device with fabrication at Sandia has produced a 252-element mirror that underwent testing at LLNL this year. Although this device has many attractive properties, optical testing showed that the pixel surface quality suffers from print-through of the underlying structures. Also, the stroke of the device (0.65 microns for a 20 V input signal) is not adequate for most vision science or astronomy applications.

Devices designed at BU and fabricated at Cronos Integrated Microsystems (CIM) were shown to have three times higher stroke than the AFRL device. The 140-actuator BU device (completed in Year 1) with a continuous surface membrane was tested in the LLNL AO testbed in Year 2, and was shown to have surface quality of ~30 nm rms after active flattening, as illustrated in Figure 2-26. This device achieved a Strehl ratio of 0.43 at a wavelength of 594 nm in the LLNL AO testbed. As a consequence of its higher stroke, continuous surface and good optical quality, we selected the BU device for further development. BU is now designing a next-generation device with 1024 actuators.

Figure 2-26. – Left panel: Dark-field micrograph of 140-actuator MEMS deformable mirror designed at Boston University. Center panel: Interferometric surface map of this device. Surface quality is ~50 nm rms. Right panel: far-field image taken with this device in the CfAO AO testbed after adjusting actuators to achieve ~30 nm rms surface quality. Measured Strehl ratio of this image is 0.43 at a wavelength of 594 nm.

In a CfAO partnership cemented by a joint post-doc (a PhD astrophysicist now pursuing MEMS research for vision science applications), Lucent Technologies has been developing packaging and drive electronics for MEMS devices developed under CfAO auspices, and performing computer simulations of future MEMS designs. Current MEMS devices make electrical connection to each pixel via a wire running to the edge of the device. Lucent is making its wire-bonder available to assist in CfAO projects. Several Boston University MEMS devices were packaged and wire-bonded at Lucent by our CfAO post-doc, and their dynamical response was tested using Lucent’s Doppler vibrometer. Lucent also delivered to the CfAO a set of drive electronics optimized for MEMS applications, and capable of operating a 1024-actuator device. As a result of this
collaboration, our postdoc has designed and assembled at Lucent an adaptive optics mirror testbed, financed by Lucent. This testbed will accommodate future CfAO mirrors. Our partnership with Lucent, Boston University, Boston Micromachines, the AFRL, LLNL, and Sandia National Laboratory is bringing out the best in university-industry-National Laboratory collaborations.

To address MEMS devices having more than 1024 actuators, new packaging approaches are needed. A promising solution is to place each pixel’s drive circuitry directly beneath the pixel, making all electrical connections behind the plane of the mirror surface. We are pursuing three methods to achieve this, in partnership with Stanford University, BU, Boston Micromachines Corp., LLNL, Lucent, Georgia Tech, MicroAssembly Technology, and UC Berkeley, with some new additional funding from DARPA.

Vision science applications of adaptive optics require a stroke of 8 – 12 microns, higher than that needed for astronomy. Working closely with CfAO’s vision scientists, in Year 1 a UC Berkeley graduate engineering student produced optically flat mirrors (< 6 nm rms) with a stroke of 6 microns, and maximum actuation voltage of 80 V. See Figure 2-27. In Year 2 these designs were extended to target 12-micron displacements for vision science, and 5-micron displacements for astronomy applications. Computer simulations have facilitated the design of these second-generation devices, which include low-stress actuators with lifetimes longer than $10^{11}$ cycles. Work has begun on array-transfer techniques for the assembly of a field of mirror segments. We expect to assemble arrays of these mirrors by the end of Year 2.

![Figure 2-27](image)

Figure 2-27 - Surface height map of an assembled mirror after actuator release. Surface deformations are 5.3 nm RMS

The MEMS projects under way in Year 2 will continue in Year 3. High-stroke MEMS development will be part of Theme 4; the other projects will be part of Theme 3.

2.5.1.2 Laboratory AO Test-Beds
CfAO is supporting adaptive optics testbeds at LLNL and the University of Rochester, with the goal of developing compact AO systems for vision science using liquid crystal spatial light modulators (LC SLMs) and/or MEMS deformable mirrors. These testbeds
are also providing infrastructure for obtaining additional funding to support specific medical applications of adaptive optics, which are not liable for NSF support.

Under CfAO auspices our 140-actuator Boston University MEMS device has been tested in closed loop in the LLNL AO testbed. MEMS tests in the University of Rochester AO testbed are about to begin, with the goal of comparing the performance of conventional deformable mirrors with MEMS mirrors in a vision-science laboratory.

In a collaboration between the University of Rochester, the UC Davis Department of Ophthalmology, and LLNL, the LLNL testbed is being used to build and demonstrate a prototype vision-science AO system based on liquid crystal spatial light modulator technology. The system is configured so that MEMS devices can be substituted for the liquid crystal devices at an appropriate time. Figure 2-28 illustrates the prototype AO system, which will be used at the UC Davis Ophthalmology Department to test the limits of visual acuity. This application of the AO testbed was supported under new funding from LLNL, obtained as a result of the CfAO’s previous investment in the testbed facility.

A second new project that was enabled by the CfAO’s testbed is a national consortium to develop and test clinical ophthalmic instruments for medical applications using MEMS AO. Participants include the University of Rochester, UC Berkeley, LLNL, the Medical Centers at UC Davis and Johns Hopkins, the Army Aeromedical Research Laboratory, and Bausch and Lomb. This project is funded by the DOE Biomedical Engineering Program to build clinical AO instruments and evaluate the effectiveness of AO in specific diagnostic protocols for diseases that cause blindness. It will also develop clinical procedures for high-resolution retinal imaging and vision correction, and compare the
vision correction obtained via laser refractive surgery and custom contact lenses with the correction obtained looking through the AO system.

2.5.1.3 Next-generation Infrared Detectors for Wavefront Sensing
Infrared wavefront sensors will allow astronomical AO systems to function even in regions of the sky where there are no visible-light natural guide stars. For example, dark clouds where dust grains preferentially absorb visible light can be nurseries for star formation, and hence of considerable astronomical interest. Until recently, infrared arrays had too much read-noise to effectively serve as high-speed wavefront sensors.

Sensitive measurements of the electronic noise of these devices will be crucial to evaluating their future utility for astronomical adaptive optics, since in many (but not all) cases laser guide star AO, using low-noise visible-light wavefront sensors, is a competitor for infrared wavefront sensing. Under CfAO sponsorship we have developed a test-stand at UCLA that is being used to test the high-speed operation of infrared arrays, and in particular to measure their electronic noise levels. The latest generation of HgCdTe arrays is now proving useful for infrared wavefront sensing; the test station is scheduled to measure the performance of sub-arrays of a HgCdTe detector before the end of Year 2. In addition, Rockwell International Science Center in Thousand Oaks CA is developing a new family of high-speed, low-noise infrared array detectors which will be evaluated on this test station.

Despite the continuing importance of infrared wavefront sensors, this project will be funded at a lower level in Year 3 because in CfAO’s transition from Goals to Themes, it was decided that other more thematically-related projects had higher priority.

2.5.2 Advanced laser technology
If only natural stars are used to measure the turbulence in the earth’s atmosphere, less than 10% of the sky is accessible to high-Strehl AO correction at near-infrared wavelengths; even smaller fractions are accessible at visible wavelengths. Laser guide stars can remedy this by creating artificial stars or “beacons” almost anywhere in the sky. They are therefore crucial for broad applications of adaptive optics in astronomy.

CfAO is currently using a first generation of custom-built dye lasers to create sodium-layer laser guide stars. These lasers tuned to the 589 nm resonance line of sodium create an artificial beacon at altitudes of 95 – 105 km in the earth’s atmosphere. The laser guide star system at Lick Observatory is working well (best Strehl ratios > 0.6 at K band); the one at Keck Observatory is scheduled for commissioning later this year. Under separate NSF auspices, a University of Illinois group is developing a Rayleigh-beacon laser guide star that utilizes a commercial pulsed excimer UV laser. While Rayleigh beacon systems are less expensive than sodium-layer systems, and the lasers are commercially available, for very large telescopes (diameter > 8-10 m) sodium-layer beacons are predicted to be superior to Rayleigh beacons.

The CfAO is pursuing two approaches to developing new lasers for sodium-layer guide stars, and in Year 3 is starting a collaboration with the University of Illinois group which
specializes in Rayleigh guide stars. Both of the sodium-laser projects are highly leveraged with our partner institutions, since new laser development and engineering is quite expensive. Both sodium-laser projects involve industrial partnerships, and one is in collaboration with an international partner, the European Southern Observatory.

In Year 3 the Center plans to organize a “laser guide star working group” which will host technical discussions of the practical issues involved in laser guide star development, deployment, and use with adaptive optics systems.

2.5.2.1 Pulsed solid-state sum-frequency laser for sodium-layer laser guide stars
The goal of this project is to produce a diode-pumped solid-state pulsed sum-frequency laser with average power > 20 watts, for use at an astronomical observatory. This University of Chicago project is co-funded by the CfAO and the Gemini Observatory (a CfAO partner institution), in an industrial partnership with LiteCycles, a Tucson, AZ-based laser company. LiteCycles is building the two gain modules, which will be tested individually first at LiteCycles and then at the University of Chicago. The University of Chicago is designing and building the sum-frequency conversion package, the 2 foot x 3 foot optical bench, an on-board control computer, and a servo system to control beam wander. The University of Chicago will do the final packaging, system integration, and testing of the sum-frequency laser. This project will continue in Year 3.

At the end of Year 1 a Preliminary Design Review was held, where it was decided to discontinue work on the original prototype sum-frequency laser so as to focus on the design and construction of the new higher-power laser. The design of the new laser is now complete. During Year 2 the diode lasers were delivered to LiteCycles. Assembly of the first gain module at LiteCycles is complete as of July 2001 (see Figure 2-29), and testing is about to begin. The University of Chicago has completed the design and construction of the laser’s optical bench and housing (which is mounted on a vertically rotating table for testing at different gravity orientations). Fabrication of the sum-frequency module is complete, as is the required test equipment. An on-board computer has been designed to control coolant flow rates and pressure. A servo system to control laser beam wander is under development.

![Gain Module Parts and Assembled Gain Module](image)

*Figure 2-29 – Photo of one of the two Lite Cycles gain modules for the sum-frequency laser. Left: Assembled gain module. Right: Gain module parts displayed on laboratory bench.*
This project had originally been scheduled for completion in April 2001, but was delayed because of late delivery of the laser diodes to LiteCycles. The revised schedule calls for testing the gain modules at LiteCycles in the summer of 2001, followed by integration and test of the sum-frequency laser at the University of Chicago in Year 3 of the CfAO.

2.5.2.2 New fiber laser for sodium-layer laser guide stars
In addition to the project described above, the Center is pursuing a longer-term project to develop a new fiber laser for laser guide star applications. The heat-dissipation characteristics of fiber lasers, their high efficiencies, excellent spatial mode characteristics, and their use of commercial telecommunications components make them a desirable candidate for high power applications.

In Year 1 the Center supported a study to identify the most promising candidate for new-generation guide star laser technology. Based on careful review of the results, a CW fiber laser system has been designed. This laser is based on sum-frequency mixing: combining an Er: doped fiber laser operating at 1583 nm with a 938 nm Nd:silica fiber laser, to generate 589 nm light via sum-frequency mixing in a periodically poled crystal. In Year 2 the technical issues associated with the 1583 nm fiber laser, the 938 nm fiber laser, and the scaling of periodically poled materials to high average power were identified and addressed. Solutions were found to each of the technical challenges. Component procurement is under way, and will be completed early in Year 3. Towards the end of Year 2 and continuing in Year 3, the individual component technologies will be demonstrated. In Year 3 the components will be integrated to demonstrate a 5-10 W, 589 nm laser system. Tests will be performed to characterize the overall laser system, and to assess future scaling to higher power levels.

Erbium doped fiber lasers are widely used in the telecommunications industry. Their lasing bandwidth is broad enough to encompass the 1583 nm wavelength. The 938 nm Nd:silica fiber is a more novel device, since the Nd³⁺ ions must operate on the resonance transition while suppressing amplified spontaneous emission (ASE) losses at the more conventional 1080 nm transition. Several methods to circumvent this difficulty were identified in Year 2: 1) By pumping the amplifier with a high power 938 nm seed pulse and using a low numerical aperture fiber, one can extract gain preferentially at 938 nm. Such a seed laser diode is available from TUI, Inc., and will be procured and loaned to the CfAO by our partner in this work, the European Southern Observatory. 2) Losses at 1080 nm can be selectively induced by bending the fiber without negatively impacting the gain at 938 nm. 3) Lowering the operating temperature of the fiber amplifier will provide a factor of 100 preference of the 938 nm transition over the 1080 nm transition. 4) Long period fiber Bragg gratings can be used to induce loss at 1080 nm.

On the basis of data obtained in Year 2, a cladding-pumped 938 nm fiber amplifier was designed. A partnership with Fibercore was established, and they have agreed to pull a specialty fiber for the 938 nm laser. IHTP in Germany has expressed interest in participating in fiber development using a different fabrication technique. The European Southern Observatory will fund the latter development and will provide the CfAO with a prototype fiber for testing later this year.
The final technical challenge is scaling the periodically poled nonlinear materials to high average power. To date, materials such as PPLN have been demonstrated at 6 W CW at visible wavelengths. Elliptical beam formats should allow powers up to 10 watts CW. The design parameters required to procure samples of PPLN, PPLT and PPKTP for elliptical beam formatting tests have been modeled. Substrates of the most promising materials were ordered; the LLNL group will pole them once they arrive. The goal is to demonstrate elliptical formatting techniques, to measure conversion efficiency as a function of input power, and to determine the maximum operating threshold. Lifetime tests will be performed to measure the robustness of the materials.

As part of the CfAO’s partnership with the European Southern Observatory, a European postdoc will join the fiber laser effort in the near future. In addition, the CfAO has established a collaboration with Professor Donald Lyons of Hampton University (an HBCU) to develop fiber Bragg gratings for the 938 nm laser, and to support a minority graduate student. The CfAO plans to continue to support this project in Year 3. LLNL provided internal funding to support aspects of fiber laser development in Year 2 and is expected to continue its support in Year 3.

2.5.2.3 Rayleigh guide stars: a new collaboration
In Years 1 and 2 the CfAO concentrated on the above two approaches to sodium-layer laser guide stars, motivated by their application to the current generation of new 8-10m telescopes. In Year 3 the CfAO plans to add a new collaboration with a U. of Illinois group developing a Rayleigh guide star adaptive optics system at Mt. Wilson, CA.

2.5.3 Adaptive optics systems for extremely large telescopes
The National Academy of Sciences’ decadal study on astronomy and astrophysics has recommended design and construction of a 30-m “Giant Segmented Mirror Telescope.” The adaptive optics system for such a telescope will incorporate features significantly more sophisticated than those used today. These include multiple laser guide stars to avoid the cone effect, multiconjugate adaptive optics using multiple deformable mirrors (each conjugate to a different atmospheric turbulence layer), and tomography algorithms to reconstruct the three dimensional structure of turbulence above the telescope. In Year 2 the CfAO investigated several important design issues for such adaptive optics systems. Researchers from four CfAO nodes UCSD, UCSC, UCI and Caltech and from the Gemini Observatory were involved, together with a visiting scientist from Italy who was in residence for a month.

In Year 2 the CfAO initiated this research thrust by holding a workshop (November 2000) for working-level technical discussions of MCAO theory, simulations, experiments, and system designs. In Year 3 this topic will become one of four major themes of the Center, and will be allocated a correspondingly larger share of the total research budget and the CfAO plans to hold working group meetings twice a year.
2.5.3.1 Multiple laser guide stars and multi-conjugate adaptive optics (MCAO)

Laser guide stars are needed because there are not enough bright stars in the sky to use as wavefront references. This results from the fact that the quality of AO correction degrades significantly once the object being observed is more than 10 to 30 arc sec away from its guide star. A 589 nm sodium laser makes an artificial guide star by exciting naturally occurring sodium atoms located in an atmospheric layer lying between 95 and 105 km altitude. However the rays of light reaching the telescope from a light-source at 100 km altitude do not measure all the turbulence above the telescope mirror; the region outside the “cone” shown in Figure 2-30a is un-sensed.

Figure 2-30. – Left panel: a) Geometry of a single laser guide star. Turbulence in the region outside the “cone” of light from the laser is not measured. This is called the “cone effect.” Right panel: b) Multiple laser guide stars, if appropriately placed, can both overcome the cone effect, and with use of multiple deformable mirrors can broaden the field of view over which the adaptive optics system gives good correction.

Use of several laser guide stars to probe the whole volume above the telescope can greatly reduce the cone effect. In addition one can increase the corrected field of view of the adaptive optics system, since a larger volume of turbulence can be measured by placing the lasers farther apart. This method is sometimes called turbulence tomography. To correct the larger volume, several deformable mirrors are needed, each optically conjugated to different heights in the atmosphere. This is called multi-conjugate adaptive optics (MCAO). In Year 2 the Center has studied fundamental questions related to two potential ways to implement MCAO on extremely large telescopes. This necessitated an end-to-end MCAO simulation code being developed and tested, in collaboration with Gemini Observatory, one of the CfAO’s partner institutions. Results from one of these simulations are illustrated in Figure 2-31.
Figure 2-31. - Effects of anisoplanatism. On the left figure, a stellar field containing ~ 1000 stars, 80’’ on a side (J band) without AO is shown. The middle image shows the effect of conventional AO. Images of the stars are point-like at the center of the field of view, but correction quality degrades at the edges of the field. The right hand side image shows an MCAO system’s performance. The field of view where high AO correction is maintained is much larger. All the stars are now resolved within this field of view.

2.5.3.1.1 The “conventional” MCAO approach
In this approach there are multiple wavefront sensors, each optically conjugated to the ground. A particular problem that arises when using several laser guide stars is as follows. The tilt of each individual laser guide star is not known a priori, since the laser passes both up and down through the atmosphere whereas starlight passes only down. When several laser guide stars are used, this tilt indeterminacy propagates into low order modes (defocus, astigmatism), which cannot be measured by the laser guide stars. In Year 2, two potential solutions were investigated: 1) using a faint natural guide star from which tip, tilt, defocus, and astigmatism (5 modes in all) are measured; or 2) using 3 or more natural guide stars, from which only tip and tilt are measured.

The conclusions of these studies were:
- Method 2) is more appropriate if highly stable AO correction is needed.
- Method 1) yields higher correction quality in the center of the field, but decays more rapidly than method 2) as one goes farther off-axis.
- Since more modes must be measured in method 1), stars must be about 2 magnitudes brighter than with method 2), for an 8 m telescope working in the infrared.
Calculations are under way to see which method provides the higher sky coverage.

2.5.3.1.2 The layer-oriented approach
This approach uses a wavefront sensor conjugated to the deformable mirrors. By using a clever optical scheme, light from all the guide stars can be co-added onto one wavefront sensor. This has the advantage of combining the light of several guide stars onto one detector, presumably increasing sensitivity. Most of the work on layer-oriented wavefront sensing has been done assuming several natural guide stars (rather than laser guide stars). To compare calculations and computer simulations with real data, an experiment was designed to assess whether the Keck Telescope Phasing Camera System could be used to test various tomography approaches, and to obtain information about profiles of atmospheric turbulence versus height at Mauna Kea. Test data were obtained in October 2000. However subsequent analysis showed that the off-axis optical quality of the Phasing Camera System was not sufficiently high for this experiment to produce useful results.
2.5.3.1.3 Partial MCAO correction over a wide field of view

Very wide field of view MCAO corrections (e.g. > 1 deg) are important for two reasons: (1) Even small Strehl improvements can have dramatic impacts on some astronomical projects (e.g. weak gravitational lensing), but only if these partial corrections are done over a very wide field of view. (2) Wide field AO correction would allow the use of only natural guide stars for MCAO over a large portion of the sky, and might thus avoid the need for lasers and their added cost and complexity.

It was found that the manner in which the wavefront is corrected has a dramatic impact on the residual wavefront error when doing partial MCAO adaptive optics. Residual wavefront errors can be reduced by up to a factor of two by adopting a layer-oriented correction scheme instead of a more traditional tomographic approach. These methods, of course, give similar results when the goal is to achieve high Strehl ratio. The reasons for such differences are still being investigated.

2.5.3.1.4 Height-invariant wavefront sensor

From a technical point of view, Rayleigh-beacons are easier and less expensive to build than sodium lasers. In Year 2 a new wavefront-sensing concept to optimize Rayleigh-beacon AO was investigated. The goal was to use all the light coming back from a (non-time-gated) Rayleigh beacon. It was found that one could put an optical element in the focal plane area whose cross-section does not change for conjugation to different altitudes. If one builds a series of such optical elements, each connected to a layer-oriented wavefront sensor, one could utilize much of the light returned from a Rayleigh beacon without need for time-gating or complex pulse formats (it will also work with a continuous beam). The current optical/mechanical design appears to be too complex to build, but there may well be a whole class of wavefront sensors similar in concept, and having more practical designs. If so, such a wavefront sensor would dramatically simplify the construction of MCAO systems based on Rayleigh-beacon lasers.
3. Education

3.1. Educational Objectives
The Education and Human Resources program has undergone considerable restructuring. A primary reason for this is to support the integration of CfAO research with the Center’s entire range of Education and Human Resources (EHR) activities. Under the new structure, the Center’s EHR program now spans all of the CfAO research themes, with education projects and activities developed in close collaboration with the theme leaders.

The four goals of CfAO’s Education activities are to:
1. Increase the versatility of Center graduate students and postdoctoral researchers through exposure and training in the diverse fields within the CfAO research and education programs.
2. Increase the number of underrepresented students from partner high schools who are prepared and motivated to pursue an SMET degree in college (2-year or 4-year).
3. Establish a center-based model for the retention and advancement of underrepresented college students, or potential college students, into the scientific or technical workforce, or next educational level.
4. Increase the interest in and knowledge of CfAO science and technology in the broader community, with a focus on high school and college levels.

Funds have been set aside in the EHR budget for Education professionals to evaluate and report on the EHR programs.

3.2 Problems Encountered reaching Education Goals
The transition to a new education philosophy, based on a more tightly defined set of goals than in Year 1, has been difficult. It has meant the discontinuance of several Education projects that had served the Center well and this resulted in varying degrees of unhappiness for those affected. The challenge now, as articulated eloquently by the EAB, is to create a CfAO “education community” that has collegial exchanges, better communications, and includes additional education professionals in its ranks.

3.3 The Center's Internal Educational Activities

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Annual Professional Development Conference</th>
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<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</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>25</td>
</tr>
</tbody>
</table>
**Goal:** 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:** In April 2001, CfAO held its first annual Professional Development Conference. Graduate student and postdoc attendees represented both astronomy and vision science. Participants visited the Gemini and Keck observatories on Mauna Kea; attended a Center-sponsored workshop on inquiry-based learning; and presented non-technical posters to local high school teachers. The conference provided an opportunity for participants to develop inter-disciplinary ties and establish contacts for future collaborations.

![Building a “Bubble Tower” – An exercise in Inquiry Based Learning](image)

**Outcomes:** An evaluation of the conference by Dr. Barbara Goza (Director, Research and Evaluation, Educational Partnership Center) is available. Initial participant responses were extremely positive, and follow-up interviews are planned to evaluate how the workshop affected EHR educational activities. Immediate outcomes are:

1. Lynn Raschke (UCSC graduate student) presented several posters and gave a short presentation at the Hawaii Science Teachers Association (4/01) after having met and established a rapport with teachers who attended the CfAO conference.

2. Sasha Hinkley (UCSC graduate student) incorporated elements of his inquiry based learning experience into his “Table Top Optics” session taught during Stars, Sight and Science (see Section 3.4).

3. The format and content of the CfAO Annual Summer School was modified to include more problem-solving and education sessions, as a result of input by conference participants.
### Mini-Grant Project

**Activity Name:** Mini-Grant Project  
**Led by:** Lisa Hunter  
**Intended Audience:** All CfAO graduate students and postdoctoral researchers  
**Approx Number of Attendees (if appl.):**

**Goal:** 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:** The Mini-Grant Project is designed to facilitate exchanges between vision science, astronomy and education and was announced at the Annual Professional Development conference in April 2001. Graduate students and postdoctoral researchers were invited to submit one-page proposals outlining a visit to a CfAO site designed to gain experience in a different discipline: for example astronomers visiting vision science sites and vice versa. Two participants subsequently submitted grant applications. In Year Three more graduate students and postdoctoral researchers will be encouraged to participate and take advantage of the opportunity. Training partnerships with educators will be encouraged.

**Outcomes:** Two mini-grants were awarded.

### Second Annual Summer School on Adaptive Optics

**Activity Name:** Second Annual Summer School on Adaptive Optics  
**Led by:** Andreas Quirrenbach  
**Intended Audience:** All professionals interested in Adaptive Optics – US graduate students and postdocs are specifically targeted.  
**Approx Number of Attendees (if appl.):** 96

**Goal:** To disseminate knowledge of Adaptive Optics to US Researchers in particular and researchers in general.

**Project Description:** The workshop is held at the UCSC campus over a period of six days: August 4 – August 10, 2001. Participants attend both lectures and laboratory sessions. The subject matter is aimed at both Astronomy and Vision Science researchers. A major focus of this year’s workshop is on MEMS technology and image processing techniques. Computer lab sessions will introduce participants to the programs used for image enhancement. A visit to the Lick observatory at Mt. Hamilton is scheduled. Approximately 80 per cent of attendees this year are CfAO graduate students and post docs. All travel expenses for CfAO attendees are covered by the Center. The fee for attending the conference plus board and lodging for the six days is $200. Speakers are primarily from the CfAO and include graduate students and postdocs.
3.4 The Center's External Educational Activities

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Stars, Sight, and Science Summer Course</th>
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<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Primarily under-represented high school students</td>
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**GOAL:** Increase the number of underrepresented students from partner high schools who are prepared and motivated to pursue a SMET degree in college (2-year or 4-year)

**Project Description:**
The four-week summer immersion experience included three coordinated courses (below) on vision science, astronomy, and science communication developed by CfAO:

1. Astronomy Today: Observing the Universe
3. Science Communication

The summer session is offered in conjunction with the California State Summer School for Mathematics and Science (COSMOS) program at UCSC. The project is also a partnership with the UCSC-based Educational Partnership Center (EPC), and builds on EPC’s relationships with three area high schools—Watsonville High School, Overfelt High School (San Jose), and North Salinas High School—all of which have large underrepresented minority student populations. In Year Three we will expand the program with pre-and post course support elements and strengthen the partnership. The Year 2 cohort of students have been encouraged to continue contact with CfAO and proactive mentoring of them will continue in Year 3.

![Student from Overfelt High in San Jose, dissects a cow eyeball in Stars, Sight and Science](image)

**Figure 3-2.** Student from Overfelt High in San Jose, dissects a cow eyeball in Stars, Sight and Science
The CfAO through its participation, contributed the following “value added” to COSMOS
1. Independent cohort of participants
2. Ongoing contact (COSMOS is 4-weeks only)
3. Served underrepresented students that would not otherwise have participated.
4. The CfAO independently developed and taught two courses.
5. Graduate students and postdocs put inquiry based teaching into practice.

Outcomes:
1. Cynthia Mendoza from Watsonville High School was awarded a scholarship of $1000 to attend any university; $2000 to attend an institution within the University of California system and $4000 if she attends the University of California Santa Cruz. The scholarship was for academic achievement, attitude and overall excellence during the summer session. She will be completing her Senior year next year.
2. Students will be tracked over time to assess the long-term impact of this project on their education. At the time of this report, the participants were just completing the course. An evaluation is in progress; also see “Plans for Year Three” for measurable objectives related to this goal.

<table>
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<tr>
<th>Activity Name</th>
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<td>Led by</td>
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</tr>
<tr>
<td>Intended Audience</td>
<td>Under-represented high school/middle school students</td>
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<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>32</td>
</tr>
</tbody>
</table>

Project Description:
The Space Explorers program aims to increase the interest and abilities in math and science of African American students from disadvantaged inner city school systems. The program strives to broaden the students’ base of scientific knowledge; to improve their abilities in problem solving, critical thinking and synthesis; to develop their communication skills; to enrich their awareness of career options in science and technology fields; and to increase their motivation to attend college.

Outcomes:
• Conducted weekly hands-on labs focused on optics
• One-week residential summer science camp – August 4-10, 2001. Theme is “colors.”
• Held three-day residential winter science camp at Yerkes Observatory. Labs included “Bloodless Dissection of the Eye,” “Reflections,” “Pin-hole Protractor”
• Pre-admissions college tour to Houston, TX (7-10 students)

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Community College Internships</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Lisa Hunter</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Community college undergraduates from underrepresented</td>
</tr>
</tbody>
</table>
Goal: Establish a center-based model for the retention and advancement of underrepresented college students, or potential college students, into the scientific or technical workforce, or next educational level.

Project Description:
An internship program for community college students was piloted during Year 2, providing summer research experiences for four community college students. These students worked on CfAO related projects under the guidance of CfAO members.

In addition to the research experiences, students participate in activities that prepare them for future opportunities. Students present a 15-minute oral presentation; prepare a poster; write and submit an abstract to present at a conference or symposium; meet with a transfer counselor and develop an academic plan; and prepare a personal statement. Equipped with these tools, they are prepared to apply for scholarships, attend conferences, and apply for additional research experiences.

Outcomes:
This project is currently in progress. Interns will be giving 15-minute oral presentations on August 3, 2001. During the following weeks, they will be completing posters to present at undergraduate conferences or symposia. Three students have applied to present posters at the SACNAS conference in September, 2001.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>ALU LIKE Traineeships</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Claire Max and Doug Knight</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Native Hawaiian Community college students/recent high school graduates</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td>2 annually</td>
</tr>
</tbody>
</table>

Project Description:
The long-term goal of this project is to increase the participation of Native Hawaiians in the technical workforce of Hawaii, especially in the state’s astronomical observatories. To accomplish this, Native Hawaiian trainees are provided internships at LLNL, where they learn optical technician skills. They then work side-by-side with CfAO’s adaptive optics researchers (both astronomy and vision science), participating fully in actual observations and experiments to develop skills in optics and electronics. These mentor relationships and hands-on experiences integrate the educational and research elements of
the program. The project also provides intensive follow-up and counseling for past interns to support career and educational development.

A closely related goal is to work toward the development of a new Bachelors Degree program at the University of Hawaii, Hilo campus. This Engineering and Information Technology (EIET) program is being developed by UH Hilo in collaboration with the astronomical observatories on the island of Hawaii, UH Manoa, ALU LIKE, and the CfAO.

**Outcomes:**
All four trainees who have completed the traineeship are currently working in a technical field or pursuing a degree in a science or technology area in Hawaii.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th><strong>K-12 Teacher Workshops: Rainbow Connection</strong></th>
</tr>
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<tbody>
<tr>
<td>Led by</td>
<td>Eileen Engel and Bernard Sadoulet</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Middle and high school teachers</td>
</tr>
<tr>
<td>Approx Number of Attendees (if appl.)</td>
<td></td>
</tr>
</tbody>
</table>

**GOAL:** To increase the interest in and knowledge of CfAO science and technology in the broader community, with a focus on high school and college levels.

**Project Description:**
The Rainbow Connection is a professional development workshop for middle and high school teachers, co-developed by Chabot Space and Science Center (CSSC) and CfAO scientists. Teachers learn about optics through a variety of hands-on activities and presentations delivered by scientists. As a follow-up to the August, 2000 workshop, an enrichment activity was offered in April, 2001 which provided an opportunity for participating teachers to review concepts and reflect on how well they had been able to integrate workshop content into the classroom.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th><strong>Mid-West Teacher Workshops and Curriculum Development</strong></th>
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<tbody>
<tr>
<td>Led by</td>
<td>Randy Landsberg and Doug Arion</td>
</tr>
<tr>
<td>Intended Audience</td>
<td>Middle and high school teachers</td>
</tr>
<tr>
<td>Approx Number of Attendees</td>
<td>Sixteen K-12 teachers</td>
</tr>
</tbody>
</table>

**Project Description:**
This project is developing a set of curricular “modules” to teach the methods of astronomical image acquisition. These curricular supplements are designed to be integrated into standard courses in astronomy and physical sciences at the middle and secondary school levels. This project addresses a gap in existing curricula in which astronomy is taught as a descriptive science with little development of the basic physical principles on which image acquisition is based.
Outcomes:
-The optics module (instructional workbook and demonstration/laboratory equipment) is now available to all participating teachers (12 total).
- Portions of the high school optics module were distributed and tested by teachers at the National Science Teachers’ Association Annual Meeting in St. Louis, MO on 3/31/01.

3.5 Summary of Professional Development Activities for Center Students
Four such activities have been described. These are:
1. Annual Professional Development Conference – A goal of the Adaptive Optics Center is to “make sparks fly between astronomy and vision science”. An essential element of this is for students from these two disciplines to meet, socialize and establish collaborations. The conference at Kona HI did much to further this goal. In addition the workshop on inquiry based learning awakened in many of these students a desire to become better teachers. Evidence of this has been shown in their interest in techniques of teaching and the application of the principles they learned at the conference to the teaching of the high school students in the Stars, Sight and Science Summer Course.
2. Mini-Grant Project - This project is designed to encourage cross-disciplinary exchanges.
3. Second Annual 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 researchers.
4. Stars, Sight, and Science Summer Course – The course is designed for under-represented high school students. However a large complement of CfAO graduate students assisted in the course as instructors. The involvement in teaching helped them apply some of the principles they had learned at Kona and sensitized them to diversity issues.

3.6 Integrating Research and Education:
All our Center members have agreed to commit 5% of their time to education. Considerable gains have been made in this area, and we continue to focus on involving members in meaningful activities that directly contribute to our educational goals. A few illustrative examples of how we have integrated research and education follow:

- Four community college students worked on CfAO related research in the summer of 2001. This number will increase to eighteen in 2002.
- Fifteen high school students and one high school teacher participated in *Stars, Sight and Science*, a course on vision science, astronomy, and optics. A special session on adaptive optics was led by graduate students Jason Porter (Rochester) and Joy Parker (Houston).
- Approximately fifteen CfAO members contributed to the instruction of *Stars, Sight and Science*.
- Twenty-five CfAO graduate students and postdocs developed non-technical posters that could communicate their research to high school science teachers.
• Inquiry-based learning was introduced to twenty-five CfAO graduate students and postdocs in spring 2001. The complexities of inquiry will continue to be a focus area.

3.7 Plans for Year Three

Overview
Our plans for Year Three reflect a major refinement and refocusing of CfAO’s educational projects that is closely tied to the overall restructuring of the Center. A range of activities will be initiated as the Center matures to create an environment that fully integrates research and education. During Year Three, activities will focus on inquiry-based teaching, paired mentoring, and the development of instructional materials that bring CfAO research into the classroom and public arena.

Paired Mentoring Project
Paired mentoring connects scientists with high school and community college teachers, to jointly mentor students who have a strong interest in science but don’t have all the supports necessary to progress smoothly through the educational pipeline. Mentoring is a key strategy for retaining students in science; however, maintaining steady contact can be challenging. The Paired Mentoring Project will employ a “double check” system by having two mentors who interact with the student individually and as a team. The paired approach will also establish a connection between the two mentors, who can become familiar with the challenges and opportunities at the other’s institution.

Inquiry-Based Teaching/Learning
“Inquiry is an approach to learning that involves a process of exploring the natural or material world, and that leads to asking questions, making discoveries, and rigorously testing those discoveries in the search for new understanding. Inquiry, as it relates to science education, should mirror as closely as possible the enterprise of doing real science.”

National Science Foundation, Division of Elementary, Secondary and Informal Education

Although scientists routinely use inquiry in their work, it is not often employed as a structure and process for teaching. The CfAO will provide inquiry models and ongoing support for the incorporation of inquiry into a variety of learning environments. We will focus on training CfAO scientists to effectively use inquiry-based teaching and matching activities to teaching goals.
4. Knowledge Transfer

All aspects of CfAO knowledge transfer in Years 1 and 2 are subsumed entirely in the combination of research Goal 2, described above, and partnerships, described in the following section (Section 5)

In Year 3, with the organizational transition to research and education themes, the CfAO will continue to emphasize knowledge transfer by employing strategies articulated in its new 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
5. Partnerships

5.1 Partnership Objectives

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

1. Coordinating and combining research efforts to take advantage of the synergies afforded by the Center mode of operations
2. Encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology
3. Leveraging our efforts through industry partnerships and cross-disciplinary collaborations
4. In addition, specific objectives for partnerships include:
5. Stimulating further investment by government and industry sources in AO research and development
6. Catalyzing the commercialization of AO technologies leading to technological advancements relevant to CfAO research objectives and enabling broader use of AO.
7. This articulation of our partnership objectives is consistent with the practices of the CfAO during years 1 and 2. In year 3, another specific partnership objective will be addressed by the Center, viz.
8. Enhancing the cohesiveness of the AO technical community, particularly with respect to system performance characterization and optimization.

Performance and management indicators that measure the success of CfAO partnership activities in meeting our objectives include:
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. (In Year 3) The number of institutional members of the AO technical community engaged in the exchange of information concerning system performance and optimization.

5.2 Problems

A challenge for the CfAO partnership activities has been attracting new industrial partners in areas involving highly competitive commercial markets, in particular, in the area of ophthalmic instrumentation. It was recognized in Year 1 that a potential factor contributing to this situation may have been the formulation of the CfAO intellectual property (IP) policy. In fact all of the CfAO review committees in Year 1 recommended a revaluation of this IP policy. Consequently, an internal committee on industrial partnerships was formed and it solicited input from the legal departments of several key CfAO nodes and the UC Office of the President. Based on the input received, the existing CfAO IP policy was reaffirmed. In brief, this policy empowers institutions
where the research is performed to develop and utilize IP in a straightforward manner consistent with the US patent laws and the normal practice of NSF. In cases where the IP may result from collaborative research between researchers in two or more institutions, the initiative for filing for patent rests with the lead institution. The distribution of licensing revenue in such arrangements will be negotiated by the IP offices of the institutions, on a case by case basis. It was acknowledged that there are other approaches to IP policy could provide a more significant role for the Center. However, after studying the original IP agreements between the nodes and the manner in which the CfAO is currently constituted, these were rejected. Along with this clarification of CfAO IP policy, the Center also confirmed its commitment to the active recruitment and effective retention of industrial partners, consistent with the overall CfAO partnership objectives.

5.3 Description of Partnership Activities

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Vision Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>David Williams</td>
</tr>
</tbody>
</table>

<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</td>
<td>AO optical bench and camera</td>
<td></td>
</tr>
</tbody>
</table>

Narrative:

Bausch & Lomb and the University of Rochester are working together on understanding the optical impact of changes in corneal shape caused by laser refractive surgery. Faculty, staff, and graduate student researchers at UR are working directly with B&L researchers and clinicians to evaluate data on LASIK patients and develop models for the effects of LASIK on the shape of the cornea and the implications for vision. As part of this effort, B&L are co-sponsoring a UR post-doctoral fellow and are part of the Alliance for Visual Excellence at the UR.

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Vision science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>Scot Olivier</td>
</tr>
</tbody>
</table>

<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 The UC Davis</td>
<td>Test new inexpensive wavefront corrector technology suitable for commercial ophthalmic instrumentation</td>
<td></td>
</tr>
<tr>
<td>Department of Ophthalmology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Multiple DOE national laboratories and multiple medical research centers</td>
<td>Develop and test prototype clinical ophthalmic instruments using MEMS adaptive optics</td>
<td></td>
</tr>
</tbody>
</table>
Narrative
LLNL has been testing MEMS deformable mirrors and liquid crystal spatial light modulators. Based on this work, which supported by the CfAO, LLNL has initiated a new collaborative project with the UC Davis Department of Ophthalmology, supported by internal LLNL funding, to assess the limits of human visual acuity using LC SLM wavefront corrector technology. This study is complementary to work being carried out under NIH funding at the University of Rochester (UR). In addition, LLNL and UR are working together, with CfAO support, on the testing of MEMS DM and LC SLM’s for correcting the aberrations of the eye. This work is being used to assess the performance of current low-cost wavefront corrector devices for prototype clinical ophthalmic applications compared with conventional deformable mirror technology. The coordination of this collaboration is facilitated by a biweekly telecon that also involves MEMS groups (see below).

Based on activities sponsored by CfAO, a collaborative team led by LLNL has been selected for support, at the level of ~$2.7M, through the DOE Biomedical Engineering Program. Over a 2 year period, this team will develop and test clinical ophthalmic instruments using MEMS adaptive optics to improve (1) the diagnosis and treatment of the diseases that cause blindness and (2) techniques for vision correction in the general population. These ophthalmic instruments will provide enhancements to the functional capabilities of several instruments currently used routinely by optometrists, ophthalmologists and retinal surgeons. Diseases addressed by these new instruments and the newly enabled clinical protocols include the main causes of blindness in the U.S.: macular degeneration, glaucoma, diabetic retinopathy, and retinitis pigmentosa.

The project team includes multiple DOE national laboratories (LLNL, SNL) and multiple medical research centers (UC Davis, University of Rochester, Johns Hopkins University, UC Berkeley) along with the Army Aeromedical Research Lab, and Bausch & Lomb. During the course of this project, the team will first develop and construct prototype clinical ophthalmic instrumentation using MEMS adaptive optics. Second, the team will develop and implement procedures for clinical high-resolution retinal imaging and vision correction. Third, the team will evaluate the effectiveness of high-resolution retinal imaging for specific diagnostic protocols for diseases that cause blindness, for specific methodologies to measure the efficacy of new treatments for these diseases, and for specific surgical protocols. Fourth, the team will evaluate visual performance obtained with adaptive optics for a wide range of subjects in the general population and compare to performance obtained with new vision correction techniques and technologies (laser refractive eye surgery, custom contact lenses). Finally, the team will investigate potential new applications of real-time, in-situ, molecular-scale, ocular imaging, including diagnosis of cancer and other diseases.

Additional support by B&L and the CfAO will be used to leverage these activities to support evaluation of the clinical utility of the version of this instrumentation that supports the vision correction functionality, and determine the suitability of this instrumentation for commercialization.
In Year 3, we plan to extend this team to solicit NIH support to enhance the functionality of the prototype clinical instrumentation to three-dimensional optical sectioning of the retina. This capability, which is currently under development in laboratory systems at the University of Houston and Indiana University with support from CfAO, is crucial for achieving the ultimate utility of high-resolution ocular imaging for bio-medical applications. This new partnership will also seek to demonstrate extensions of the biomedical protocols described above that take advantage of this three-dimensional optical sectioning capability.

<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>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Participants</th>
<th>List Shared Resources (if any)</th>
<th>Use of Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>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>
<tr>
<td>2</td>
<td>The organization of a new national consortium to develop and test MEMS spatial light modulators, scalable to 1k × 1k pixels, for holographic wavefront correction suitable for application to laser communications and high-resolution imaging.</td>
<td></td>
</tr>
</tbody>
</table>

Narrative:
The CfAO supports a coordinated national consortium of universities (UC Berkeley, Boston University, UC Davis, Stanford University), national laboratories (LLNL, SNL, AFRL, JPL) and industrial partners (Lucent, Boston Micromachines, JDS Uniphase, Intellite) to develop MEMS deformable mirror technology for adaptive optics suitable for application to vision science and astronomy. Coordination of this consortium is facilitated by an annual meeting, held in November, and by a monthly telecon, now being held in conjunction with the vision science telecon (see above). Moving into Year 3, much of the emphasis of the MEMS development program is on the production of a MEMS device suitable for application to a commercially viable clinical ophthalmic instrument. The MEMS groups are therefore now actively interacting with the vision science groups, especially the University of Rochester, in order to understand the requirements for ophthalmic wavefront correction.

At UC Berkeley College of Engineering, the Berkeley Sensor and Actuator Center (BSAC), an NSF Industry/University Cooperative Research Center, has been active in the design and fabrication of new MEMS deformable mirror devices with high stroke, an important characteristic for both astronomy and vision science. BSAC has also investigated novel methods for bonding mirror and actuator arrays. The advantage of this approach is it allows more flexibility in the design and fabrication of both the mirror and
actuator arrays that may enable devices with more desirable characteristics, e.g., higher stroke and better optical quality. In Year three, these activities will be focussed on the adaptation of these designs using a fabrication process that will allow more direct integration with drive electronics, thereby producing a more attractive device for application to clinical ophthalmic instrumentation. An early version of this device may use drive electronics provided by Lucent. When completed, and after characterization at BSAC, initial system demonstration of these devices will be carried out at LLNL and/or Rochester.

UC Berkeley also maintains a post-doctoral researcher resident at Lucent Bell Labs. The focus of this partnership is to utilize the MEMS packaging and drive electronics technology developed by Lucent. This technology has been developed for an optical cross-connect switch product line at Lucent and will be used by the CfAO for the MEMS deformable mirrors being developed by other CfAO institutions and partner organizations. As part of this partnership, components of a 1000-channel drive electronics system have been delivered to LLNL, and are ready for integration with MEMS devices. In Year 3, another goal of this partnership will be to utilize MEMS fabrication process technology being developed at Lucent for membrane mirrors in order to produce a new type of MEMS deformable mirror device with characteristics suitable for application to clinical ophthalmic instrumentation. When completed, and after characterization at Lucent, system demonstration of these devices will be carried out at LLNL and/or Rochester. Lucent has also funded the development of their own AO system test-bed facilities to evaluate devices developed at Lucent and elsewhere.

The Air Force Research Lab (AFRL) at Wright-Patterson Air Force Base has been active in the design of MEMS deformable mirrors for the CfAO. These devices were fabricated in the MEMS foundry facility at Sandia National Laboratory, and were subsequently tested at LLNL. Although this device has many attractive properties, optical testing showed that the pixel surface quality suffers from print-through of the underlying structures. Also, the stroke of this device (0.65 microns for a 20 V input signal) is not adequate for most vision science or astronomy applications.

Boston University and a spin-off company, Boston Micromachines Corporation (BMC) have been working with the CfAO to provide MEMS deformable mirrors for testing and evaluation. These mirrors are fabricated at the JDS Uniphase MEMS Business Unit (formerly Cronos Integrated Microsystems). Several have been characterized at LLNL, with the participation of a UC Davis graduate student, and show good optical quality and other characteristics. A small number are now being evaluated in the vision science test-bed at the University of Rochester, and are the leading candidates to be used for the first version of a prototype clinical ophthalmic instrument. Some of these mirrors have also been packaged at Lucent in an automated process that could eventually improve the yield for integrated devices.

In Year 3, the CfAO will provide seed funding to JPL to work with the Center to assess the suitability of MEMS deformable mirrors being developed at JPL for application to clinical ophthalmic instrumentation.
LLNL continues to lead the coordination of this consortium. In addition, with the participation of a UC Davis graduate student, LLNL has characterized mirrors designed by BU/BMC and AFRL. LLNL has also begun to work with Stanford University and a spin-off company, Intellite, on the development of MEMS mirrors suitable for application to clinical ophthalmic instrumentation. In Year 3, LLNL will also work with BU & BMC to develop and test MEMS devices with more actuators, suitable for application to eXtreme AO for ultra-high-contrast astronomical observations.

Based on activities sponsored by CfAO, a collaborative team led by LLNL has been selected for support, at the level of ~$9.5M, through the DARPA Coherent Communications, Imaging and Targeting Program. This team will develop powerful new capabilities for secure free-space communication links (multi Gb/sec) and aberration-free, 3-dimensional, imaging and targeting at very long ranges. Innovative concepts and integration of micro-electromechanical-systems (MEMS) spatial light modulators, along with photonics and high-speed electronics will provide affordable and high value systems for use well into the 21st century. Phase-I of the two-phase program will be executed by a team consisting of the Lawrence Livermore National Laboratory (Phase-I lead), academic institutions (Boston University, Stanford, Berkeley, Georgia Institute of Technology), MEMS/photonics companies (Boston Micromachines, Lucent, Maxios, MicroAssembly Technologies) and U.S. aerospace companies (Ball Aerospace, Boeing, Harris, HRL Laboratories, Northrop Grumman, Raytheon, TRW and the Aerospace Corporation). The primary role of the aerospace companies will be as potential users and competitors for Phase-II, which will be led by industry. HRL Laboratories and TRW are also contributing to Phase-I hardware development and applications/systems modeling. Phase-I funding is over a two-year period.

In addition to these partnership activities, LLNL has been selected to receive seed funding, at the level of ~$350K, from the NRO DII project to demonstrate fabrication technologies for large MEMS deformable mirrors for lightweight space telescopes. This 9-month project will be performed in collaboration with Stanford University and a spin-off company, Intellite. The CfAO (primarily UCSC, LLNL and Gemini) is also proposing a new collaboration in partnership with the Air Force Maui Optical Station to be supported by the AFOSR. The research areas identified are (i) deconvolution and super-resolution, (ii) atmospheric simulations, (iii) fast wavefront reconstruction algorithms, (iv) improvements to the AEOS adaptive optics performance, and (v) application to wavefront control using micro-electromechanical systems (MEMS) technology.

<table>
<thead>
<tr>
<th>Partnership Activity</th>
<th>Lasers</th>
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<tbody>
<tr>
<td>Led by</td>
<td>1. Edward Kibblewhite; 2. Deanna Pennington</td>
</tr>
<tr>
<td>Participants</td>
<td></td>
</tr>
<tr>
<td>Name of Organization</td>
<td>List Shared Resources (if any)</td>
</tr>
</tbody>
</table>

European Southern Observatory
Hampton University, Ionas, IRE Poulus Group, TuiOptics, Fibercore and the IPHT fiber institute in Jena, Germany.

Narrative:
Lite Cycles has been working with the University of Chicago to produce improved solid state laser heads for a sum-frequency laser being developed at Chicago based on a design originally from MIT Lincoln Labs. Coherent is working on a contract from Gemini to develop another approach for an improved laser head for this type of laser. AFRL is working with Lightwave Electronics on another laser head variation for this laser concept.

LLNL also has a project within the CfAO to study fiber lasers. Complementary aspects of this work have been supported by internal funding at LLNL at the $221K level in FY 00. A patent was applied for: "Synthetic Guide Star Generation," S. A. Payne, R. H. Page, C. A. Ebbers, and R. J. Beach, Patent # IL-10737, submitted April 2001. An international collaboration has been established with the European Southern Observatory to jointly pursue this research. This has resulted in the provision of equipment and manpower by ESO to complete the research. A collaboration has been established with Hampton University, a historically black university, to support a minority graduate student to develop fiber Bragg gratings for the project. Significant industrial contacts have been established to produce the new custom technology components required for this research, namely Ionas, IRE Poulus Group, TuiOptics, Fibercore and the IPHT fiber institute in Jena, Germany.

5.4 Other Partnership Activities
In the area of support of existing astronomical AO systems, partner institutions include the Gemini Telescope Project, the W. M. Keck Observatory, LLNL (Lick and Keck Observatories), and JPL (Palomar Observatory). These institutions are active in the maintenance of four of the most powerful AO systems in operation. In addition, LLNL and Keck Observatory are actively developing laser guide star facilities for Lick and Keck Observatories. In Year 3, the focus of these activities will be on enhancing the cohesiveness of the AO technical community, particularly with respect to system performance characterization and optimization. This process will be coordinated by the CfAO and will involve the evaluation of multiple astronomical AO systems (Lick, AEOs, ADONIS, CFHT, Palomar, Gemini, and Keck) along with the vision AO systems at Rochester and UC Davis. In addition, significant effort will be put into optimization of the Keck AO system.

In the area of design of AO systems for giant telescopes, CfAO has co-sponsored a working group with NOAO to produce a national AO technology development roadmap.
In addition, both JPL and LLNL have been active in working with the University of California and the California Institute of Technology on design concepts for AO systems on giant telescopes. In Year 3, much of the research activity within the CfAO will be explicitly focussed on this area, which will be one of the three principal research themes in the Center.

The Gemini Telescope Project has also produced a preliminary design of a multi-conjugate adaptive optics system that could dramatically increase the AO corrected field size for large telescopes. CfAO member institutions, including the University of Chicago and LLNL, participated in the Gemini MCAO preliminary design in the area of lasers and the laser launch system, along with the CfAO’s industrial partners in the laser area.

5.5 Partnership Activities - Future Plans

1. To revise and expand the vision team to solicit NIH support for extending the functionality of the prototype clinical instrumentation to three-dimensional optical sectioning of the retina.
2. To utilize MEMS fabrication process technology being developed at Lucent for membrane mirrors to produce a new type of MEMS deformable mirror device with characteristics suitable for application to clinical ophthalmic instrumentation. When completed, and after characterization at Lucent, system demonstration of these devices will be carried out at LLNL and/or Rochester.
3. Provide seed funding to JPL to work with the Center in assessing the suitability of MEMS deformable mirrors being developed at JPL for application to clinical ophthalmic instrumentation.
4. Work with BU & BMC to develop and test MEMS devices with more actuators, suitable for application to eXtreme AO for ultra-high-contrast astronomical observations.
5. Enhance the cohesiveness of the AO technical community, particularly with respect to system performance characterization and optimization.
6. Focus on design concepts for AO systems on giant telescopes - one of the three new principal research Themes in the Center.
6. Diversity

6.1. Increasing Diversity
While we are working towards increasing diversity within all areas of the Center, the initial focus will be on our student population for Year Three. We have been very successful in recruiting women into our graduate programs, and will continue to do so. In addition, our Center-wide commitment to mentoring is designed to improve the retention of women and underrepresented minorities in science programs. In Year Three we will expand Stars, Sight, and Science Summer Course with pre-and post course support elements and strengthen the partnership between ourselves and the “feeder” High Schools - Watsonville High School, Overfelt High School (San Jose), and North Salinas High School. All of these have large underrepresented minority student populations.

6.2 Problems
None of the issues that the Center faces in advancing diversity recruitment are unique to this Center. It takes discussion of the issues and careful planning to develop a foundation that is likely to yield a successful program that includes the targeted recruiting at all levels of the workforce. Part of the evaluation process for determining the success or failure of the enterprise is the implementation and maintenance of meaningful databases. For example, under-represented high school students who enter our study and mentoring programs need to be tracked over time to determine their success rate relative to the general student body or some other parameter that has meaning. Outcomes of such analysis will not be available for several years. In the shorter term the programs will be monitored by trained evaluators interviewing students, teachers, and mentors.

6.3 Center Contributions to developing US Human Resources

National Society of Black Physicists Conference 3/50/01 at Stanford University.
The Managing Director attended this conference and in particular participated in the career fair. The CfAO prepared brochures and led discussions focussed on REU opportunities at CfAO sites for the summer and research opportunities in vision science and astronomy for those wishing to attend graduate school. Several follow-up calls resulted from the contacts made.

Annual Professional Development Conference (see complete description in Section 3.3)
This conference was extremely well received by Center graduate students and postdoctoral researchers. Participants clearly indicated that the conference provided a much-needed community and new possibilities for collaboration. We will capitalize on the conference success by advertising it as one of the benefits of being a Center member. Another aspect of the conference is the development of a community within our graduate students and postdocs. We will continue to explore how a feeling of community affects retention, and how to maintain a community with members spread out across the U.S.
CfAO Faculty Fellows Program
This new project will begin in Year Three. A visiting faculty member from a Minority Serving Institution (MSI) will be hosted and financially supported for the summer at a CfAO institution. Funds are also available for the faculty member to have an undergraduate student from the MSI join him/her and share in the research experience.

SACNAS Conference (Society for Advancement of Chicanos and Native Americans in Science.)
The CfAO will continue its involvement in the SACNAS organization. SACNAS promotes a high quality annual conference and its organizational headquarters is close to that of CfAO. Our involvement will include attendance at the annual conference, leading science sessions where possible, actively promoting the participation of our students, and assisting with the student award selection committee.

New Graduate Student Fellowship
The CfAO will offer a fellowship to an incoming underrepresented graduate student at a CfAO node. This fellowship will be for $10,000 and will supplement the overall financial package offered to the student by that node. The awardee will be required to attend all CfAO professional development activities offered to our graduate students and postdocs. Our goal is to attract underrepresented graduate students into the field of adaptive optics and establish connections within our scientific community.

Paired Mentoring Project
The Paired Mentoring Project is incorporated into several educational projects at the high school and college level. CfAO members participating in this project will be sensitized to the barriers faced by underrepresented students and the experiences and support structure that helps keep students committed to their education. Mentoring will be a theme at all CfAO events, with members sharing their successes and challenges with their peers.

6.4 Plans
Describe your plans for programs or activities to enhance diversity for the next reporting period with attention to any major changes in direction or level of activity.

See 6.1 above.

6.5 Diversity Impacts
Discuss the impact of these programs or activities on enhancing diversity at the Center.
The short term impact is one of awareness and sensitivity to the issues of diversity. The Center places a high priority on increasing the diversity of its members by vigorous recruiting at all levels. In the longer term we expect the programs we are implementing to increase enrollments of under-represented students in baccalaureate science programs and in graduate programs at CfAO sites.
7. Management

7.1 Center Organization
The Year 2 organizational chart (Appendix B.1) schematically depicts the CfAO management structure for the Center in its “goal mode” of research management. This will change in Year 3 as the Center completes the transition into a theme management mode (Appendix B.2). However, the executive function will remain essentially the same in the new organization.

The Director remains the Chief Scientist, with overall responsibility for the Center activities and prime responsibility for the research conducted within the Center. The daily operational functions are the responsibility of the Managing Director, who also has overall fiscal responsibility for budgets and oversight of educational and industrial outreach activities – including intellectual property. The internal governing body of the Center is: The Executive Committee, which in year 2 was made up of the Director, Dr. Jerry Nelson; the Managing Director Dr. Chris Le Maistre, Associate Directors and Site Coordinators.

Associate Directors, Year 2

Astronomical Science, Dr. Andrea Ghez;
Vision Science, Dr. David Williams;
AO Dissemination to the Scientific Community, Dr. Andreas Quirrenbach;
Scientific Instrumentation, Dr. James Larkin;
Advanced Technology, Dr. Claire Max;
Education and Human Resources, Lisa Hunter;
External Partnerships, Dr. Scot Oliver;
Associate Director at Large, Dr. Bernard Sadoulet

Site Coordinators
Dr. Richard Dekany Caltech
Dr. Gary Chanan University of California, Irvine
Dr. James Graham University of California, Berkley
Dr. Edward Kibblewhite University of Chicago
Dr. Austin Roorda University of Houston
Dr. Donald Miller Indiana University.

Within the University of California, Santa Cruz (UCSC), the Director at the commencement of Year 2 reported to the Associate Vice Chancellor for Research. – see Appendix B. Following discussions between the university administration and members of the Executive Committee, it was decided that the Center’s interests would be best served if the Center Director reported to an Oversight Committee chaired by the Associate Vice Chancellor for Research. The members of this committee could help...
integrate the Center’s activities more with the relevant schools within UCSC. See 7.3 below.

The make-up and functions of the External Advisory Board and Program Advisory Committee remain unchanged through this transition.

The External Advisory Board (EAB) has representatives from the fields of Astronomy, Vision Science, Adaptive Optics, and Education. They provide overall advice on the research and policies of the Center. The EAB reports to the UCSC Associate Vice Chancellor for Research.

The Program Advisory Committee (PAC) provides their advice and insights into the research being pursued, both within and outside of the CfAO. The PAC reports to the Director of the CfAO.

Membership of both committees is provided in 7.5 below.

7.1.1 Transition to Themes
As mentioned, the Center in Year 2 is transitioning from a goal to a theme mode of project management which will be completed by Year 3. This reorganization resulted from the Center Executive Committee recognizing that organizing projects by goals did not sufficiently encourage researchers to work in a Center mode and to collaborate with each other. It was also difficult to identify what lasting impact the Center could have on the field of Adaptive Optics beyond the life of the Center. Finally, it was realized that the Education Program should engage all Center members and be more closely aligned to the Center’s research. This became the subject of two Retreats – one restricted to the Center Executive Committee and the other open to all Center researchers. The consensus was that a theme approach be developed that would:

1. Encourage greater collaboration between researchers.
2. Identify lasting Center monuments or achievements.
3. Develop a road map with milestones to help ensure success.
4. Foster interactions between astronomers and vision scientists.
5. Increase understanding of the Center’s educational and human resources goals on the part of all researchers and expand opportunities to share in the achievement of these goals.

A description of the four new themes follows:

Theme 1: Education And Human Resources
The Education and Human Resources program has undergone considerable restructuring. A primary reason for this is to support the integration of CfAO research with the Center’s entire range of Education and Human Resources (EHR) activities. Under the new structure, the Center’s EHR program now spans all of the CfAO research themes, with education projects and activities developed in close collaboration with the theme leaders.
The four goals of CfAO’s Education activities are to:

1. Increase the versatility of Center graduate students and postdoctoral researchers through exposure and training in the diverse fields within the CfAO research and education programs.
2. Increase the number of underrepresented students from partner high schools who are prepared and motivated to pursue an SMET degree in college (2-year or 4-year).
3. Establish a center-based model for the retention and advancement of underrepresented college students, or potential college students, into the scientific or technical workforce, or next educational level.
4. Increase the interest in and knowledge of CfAO science and technology in the broader community, with a focus on high school and college levels.

**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, or GSMT). Developing an adequate adaptive optics system for this telescope will be extremely challenging and will require developments in most technical areas of adaptive optics. Making a major contribution towards achieving this national priority is a natural and suitable objective for the CfAO. The benefits of multi-conjugate adaptive optics (MCAO) include widening the diffraction-limited field of view and achieving near-complete sky coverage with laser beacons (by overcoming the cone effect). While the ultimate implementation of a MCAO system for a 30-m telescope will require both time and resources far beyond the scope of the CfAO, we believe that we can develop the crucial concepts and components needed for its successful implementation.

**Theme 3: Extreme Adaptive Optics (eXAO): Enabling Ultra-High-Contrast Astronomical Observations**
The eXAO theme is scientifically driven by the need to achieve high-contrast imaging and spectroscopic capabilities to enhance the detection and characterization of extra-solar planetary systems and their precursor disk material. By improving image quality, eXAO systems 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.

The primary goal of this theme is to catalyze the development of the next generation of high-order adaptive optics systems in order to achieve unprecedented capabilities for high-contrast astronomy. This will require activities in eXAO system design along with the design of instruments, such as coronagraphs, optimized for high-contrast observations. Additional crucial activities include the development of new simulation
capabilities for eXAO systems and instruments, along with better characterization of the performance existing high-order AO systems, and the development of new technologies in high-order wavefront correction devices, such as MEMS deformable mirrors, and in wavefront control system algorithms and architectures. Ongoing scientific utilization of high-contrast observational capabilities and development of data processing techniques optimized for high-contrast observations are also critical activities for this theme. This theme is likely to share many cross-cutting issues with Theme 2.

**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 will be 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 AO designs.

**7.1.2 Year 3 Executive Committee Changes**

The change of the Center from the “goal” to “theme” mode of research organization resulted in changes and some reduction in size of the Executive Committee. The Executive Committee for the latter half of the transition Year 2 and for Year 3 is:

Jerry Nelson - Director
Christopher Le Maistre - Managing Director
Claire Max - Theme 2 Leader
Lisa Hunter - Associate Director E & HR (Theme 1)
Scot Olivier - Theme 3 Leader
David Williams - Theme 4 Leader
Ed Kibblewhite - Site Coordinator Representative
Andrea Ghez - Associate Director Astronomy Science
Richard Dekaney - Associate Director Multi conjugate Adaptive Optics
Austin Roorda - Associate Director Vision Science
Andreas Quirrenbach - AO Dissemination to the Scientific Community

**7.2 Performance and Management Indicators**

The Center for Adaptive Optics has sites that are widely dispersed geographically. Seven are in California and the remaining four are in Rochester, NY; Houston, Texas; Chicago, Illinois; and Bloomington, Indiana. This presents both an expense and logistical problem for management and researchers to attend meetings.

Since its inception, the Center’s Executive Committee has held regular biweekly teleconferences. The Executive Committee consists of the business, education, and science management teams. All aspects of the Center’s performance are discussed at these telecons, with appropriate action items recommended and implemented.
Our method for evaluating progress on particular projects has evolved over time - we had to learn what worked and what didn’t. In Year 1, all researchers were required to provide monthly progress reports that described progress against the milestones identified in each project’s original proposal. It became evident that monthly reporting did not work well: there was too little change from one month to the next, monthly reporting placed too much of a burden on the financial officers at each node, and many of the required reports were tardy and incomplete. To remedy this situation, in Year 2 we changed to a system of quarterly research reports. This was a substantial improvement over Year 1. However it still had room for improvement, as we did not have a rigorous system in place for the Associate Directors associated with the four Goals to review all quarterly reports for their Goal and so monitor progress against milestones. Hence in Year 3, we will move to a system in which each Theme Leader is forwarded all the quarterly reports for the projects in his or her theme, and is expected to review progress against milestones with researchers in their theme on a quarterly basis. Based on our experience over the past two years, we believe that this system will be both practical and effective.

Project evaluation also takes place during the annual proposal review process, where previous progress against milestones is an important criterion for continuation of a project’s funding in the following fiscal year. To review our Year 2 and Year 3 proposals, we constituted a Proposal Review Committee composed essentially of the Executive Committee membership. This committee reviewed all proposals and recommended funding levels to the Director. The Director has the ultimate authority for program and funding decisions.

The quarterly reports and annual reports submitted by each project are used by the Proposal Review Committee (PRC) to evaluate progress annually and, together with formal proposals for each new and ongoing project, to decide on the level of funding for each project for the following year. In reviewing the proposals for Year 3, proposals were sent to both internal and external mail reviewers prior to the meeting of the PRC. At the PRC meeting, each Theme Leader presented the background and content of each proposal in his/her Theme. Then the Theme Leader, together with a second PRC member discussed the content of the mail reviews, as well as their own reviews of the project in question. This allowed us to take into account the opinions of a substantial group of external reviewers, as well as the opinions of internal PRC members who were better equipped to comment on the Center-related aspects of each project. Each proposal was then discussed in detail by the whole PRC, which decided upon a consensus recommendation for Year 3 funding.

Starting in Year 3, the Education and Human Resources Theme will use expert consultants to evaluate its programs, in addition to the PRC process described above.

7.3 Problems
1. The move from Goals to Themes has had the effect of tipping the science/technology balance of the Center towards technology. This is natural, as advanced AO technology designs are now reaching the more costly implementation stage. This is
reflected in the funding portfolio of projects for Year 3. Science funding within the Center has diminished, and this fact has distressed the affected science researchers who had anticipated longer term funding for their science projects. The Program Review Committee made every effort to ensure that ongoing obligations to existing postdocs and graduate students were met. Where it turned out that, despite these efforts, specific students and postdocs would have difficulties in Year 3, the Center’s Executive Committee reviewed any oversight that may have occurred, and if valid, ensured that the obligation to the individual was met. Because of the transition from Goals to Themes, Year 2 has been difficult. However, the Center’s Executive Committee expects the review and evaluation process to be operating in a steady state from here on.

2. The transition to the new education philosophy has been difficult. The Education programs are now based on a more tightly defined set of goals, but this has meant the discontinuance of several Education projects, which resulted in varying degrees of unhappiness. The challenge now, as articulated eloquently by the EAB, is to create a CfAO “education community” that has collegial exchanges, better communications, and includes a few more education professionals.

3. The new CfAO building on the UCSC campus is nearing completion. Until recently, work was running behind schedule, which in turn affected the acquisition dates for video-conferencing equipment. The downturn in the dot.com economy increased the availability of local construction workers and a mid-October opening day is now predicted.

4. Although there have been delays in placing the order for video-conferencing equipment, we have been using the video-conferencing facilities available on campus to communicate with both the NSF and some of the other CfAO nodes. The delays in purchasing have had a fortuitous benefit in that the field is rapidly developing and many more desirable features are now being provided at no additional cost.

5. Difficulties have been experienced in working with the Laser Refractive Surgery companies, since they are VERY competitive with each other and won’t divulge details of how well their AO development work is proceeding. Despite this, the Center has made some positive contacts with several companies.

6. The “AO for ELT’s” theme has to build relationships with all the other major players in MCAO (Gemini, Europeans, etc), and find ways in which the CfAO can “take the lead” in developing an AO roadmap for ELTs (as recommended in the EAB report).

7.4 Management and Communication Systems
The Center’s management of research and its EHR programs has been described above. The Center has employed a full time financial analyst. This position is responsible for the fiscal health of the Center and the financial analyst communicates frequently with the Business managers at each site.

Because the eleven sites constituting the Center are geographically widespread, the Center is investing in video-conferencing facilities at each site. A Request for Proposals (RFP) was sent to vendors early in the spring. A vendor has been identified and a system selected. All systems should be installed and running by the Fall of 2001. At the Santa Cruz campus, the system will be installed in the new CfAO building, which should be
ready for occupancy in mid-October 2001. In addition to the Executive Committee meeting bi-weekly via video-conference, the Center will sponsor AO Science seminars at which graduate students and postdocs make weekly research presentations to the Center via video-conference.

The Center Director and his staff has already been using a video-conferencing facility on the Santa Cruz campus to have monthly meetings with our Technical Coordinator and other officers at the National Science Foundation. We have found these meetings to be mutually beneficial and hope to continue them into the foreseeable future.

### 7.5 Center’s Internal and External Advisory Committees

**Internal Oversight Committee – University of California Santa Cruz**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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</thead>
<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 Joyce Justus</td>
<td>Chair, Department of Education</td>
</tr>
</tbody>
</table>

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

**External Committees**

The Center has two external committees:

*The Program Advisory Committee and The External Advisory Board*

**The Program Advisory Committee**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>1 Dr. James Belectic (Chair)</td>
<td>W. M. Keck Observatory</td>
</tr>
<tr>
<td>2 Dr. Mark Colavita</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>3 Dr. Stanley Klein</td>
<td>University of California, Berkeley</td>
</tr>
<tr>
<td>4 Dr. Steven Vogt</td>
<td>University of California, Santa Cruz</td>
</tr>
<tr>
<td>5 Dr. Anneila Sargent</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>6 Dr. Joyce Justus</td>
<td>University of California, Santa Cruz</td>
</tr>
<tr>
<td>7 Dr. Francisco Hernandez</td>
<td>University of California, Santa Cruz</td>
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</tbody>
</table>

**The External Advisory Board**

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<tr>
<th>Name</th>
<th>Affiliation</th>
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</thead>
<tbody>
<tr>
<td>1 Dr. Christopher Dainty (Chair)</td>
<td>Imperial College, London</td>
</tr>
<tr>
<td>2 Dr. Pablo Artal</td>
<td>Universidad de Murcia, Spain</td>
</tr>
<tr>
<td>3 Dr. Goery Delacote</td>
<td>The Exploratorium, San Francisco.</td>
</tr>
</tbody>
</table>
7.6 The Center’s Strategic Plan

During the two Retreats in February and March of Year 2, a Mission statement was formalized.

**CfAO Mission and Goals**

A statement of mission and goals was developed and endorsed by the Center membership in March 2001:

**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.

The Center has developed a Strategic Plan based on this Mission Statement. The Plan lays out the four Themes described in Section 7.1.1. Each Theme has developed a road map with short and long term milestones.
8. Center-wide Output and Issues

8.1 Center Publications


8. “Retinal imaging and vision at the frontiers of adaptive optics,” Donald T. Miller, Parity, 15, 22-29.


8.2 Conferences


31. “What Determines Unique Yellow, L/M Cone Ratio or Visual Experience?” Yamauchi, Y, Williams, D. R., Brainard, D. H., Roorda, A., Carrol, J., Neitz, M.,
8.3 Dissemination Activities

1. November 6-8, 2000 - Education/Science Retreat held in Santa Cruz. Eighty one CfAO participants discussed research, education and issues arising from the NSF Site Visit. This was the launching point for subsequent discussions that led to the Center’s transition towards a “themes” based management of research.

2. November 13, 2000 - 2nd Annual MEMS Development Meeting. The meeting reviewed MEMS development efforts by participants in the fields of applications for Vision Science, Communications, and Astronomy. 20 people attended.

3. November 21, 2001 – Workshop on Multiconjugate Adaptive Optics. This workshop had international attendance with 22 people.

4. January 2001 - The CfAO was a major contributor to an NSF "Seminar for Science Writers” on Adaptive Optics, at the American Astronomical Society meeting in San Diego, CA, and prepared the main press brochure introducing the basic concepts of adaptive optics.


6. February, 2001 - The CfAO was a joint organizer, with the National Optical Astronomy Observatories, of a workshop on methods for reducing Hokupa’a adaptive optics data.

7. February 11, 2001 in Monterey, CA - Austin Roorda organized a workshop entitled "Calibration of Wavefront Sensors for the Human Eye" which was part of the 2nd International Congress on Wavefront Sensing and Aberration-free Refractive Correction. The workshop was attended by 136 vision scientists, refractive eye surgeons and commercial manufacturers. Scot Oliver opened the workshop and discussed the purpose of the CfAO. A featured speaker was Scot Acton from the Keck Observatory. Twelve speakers gave talks on the calibration of wavefront sensors for the human eye.

8. February 11–13, 2001 – Executive Committee Retreat. Twenty people attended and discussions were held resulting in plans for Center reorganization.

9. February 20, 2001 – Workshop on Advanced Mirror Coatings (co-sponsored by the CfAO and the California Extremely Large Telescope, or CELT)

10. March 3-4, 2001 – Spring Retreat at Caltech. Fifty nine researchers from the Center attended. Plans for Center re-organization were introduced, discussed, and approved by the Center membership.

11. March 22, 2001 - Workshop on Extremely High Contrast AO . The workshop covered observational results with existing AO systems and analytical and numerical predictions on the performance of next-generation AO coronography systems. Numerical simulation and laboratory results from high-contrast imaging work ongoing in the space telescope community were also presented and discussed. Over 24 people participated.

12. April 18-23 2001 - Integrating Research and Education. This graduate student and postdoc workshop, held in Kona, Hawaii, had 40 participants from both our vision science and astronomy communities. Attendees visited Keck and Gemini observatories, presented two poster sessions, and attended a workshop on Inquiry Based Learning.
13. July 1 – 7, 2001 - The COSMOS summer program for High School students from under represented groups. Held in Santa Cruz, CA. Instructors from CfAO included five faculty, one postdoc and seven graduate students and staff. Thirty five “Rubber Eyes” from the University of Houston College of Optometry were made and delivered to this summer program.

14. Summer 2001 - B. Macintosh (LLNL) organized a seminar series for undergraduates at IGPP/LLNL.

15. July 25, 2001 - Adaptive Optics for Extremely Large Telescopes. This workshop included a discussion of mid IR detectors for future instruments, reviewed several potential AO types for ELT’s, discussed Rayleigh backgrounds from laser beacons, and discussed in some detail the technical requirements imposed by MCAO. Seven people attended.

16. July 25 2001 - David Williams gave a presentation on Adaptive Optics for the Eye to the American Association of Physics Teachers. This talk summarized the vision science theme of CfAO.

17. July 26, 2001 - Atmospheric Characterization Workshop. 17 participants from in and outside of the Center attended. The discussions aimed at stimulating collaborative research on this topic within the Center.

18. August 4-10, 2001 – Second Annual Summer School on Adaptive Optics held at the Univ. of California, Santa Cruz. Ninety six participants registered. Most of the speakers and instructors are drawn from the CfAO PIs, post docs, graduate students and research scientists.


20. Casper Maheshwaris from the U. of Rochester prepared and tested a learning package for undergraduates taking introductory physics called "Learning Optics using Vision".

### 8.4 Awards

<table>
<thead>
<tr>
<th>Recipient</th>
<th>Reason for Award</th>
<th>Award Name and Contributor</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 S. Faber</td>
<td>Science Achievement</td>
<td>American Philosophical Society</td>
<td>2001</td>
</tr>
<tr>
<td>2 Claire Max</td>
<td>To recognize and promote the scientific accomplishments of the recipients, who have made pioneering advances in their fields of expertise</td>
<td>Edward Teller Fellowship, Sponsor: Director of Lawrence Livermore National Laboratory</td>
<td>2001</td>
</tr>
<tr>
<td>3 Donald T. Miller</td>
<td>Outstanding teacher</td>
<td>Trustees' Teaching Award at Indiana University</td>
<td>2001</td>
</tr>
<tr>
<td>4 James Larkin</td>
<td>Sloan Research Fellow</td>
<td>University of California, Los Angeles</td>
<td>2000-2002</td>
</tr>
<tr>
<td>5 Fan Zhou</td>
<td>academically outstanding graduate, student</td>
<td>Chancellor’s Fellowship from Indiana University</td>
<td>2001</td>
</tr>
<tr>
<td>6 Tiffany Glassman</td>
<td>UCLA Dissertation Year Fellowship</td>
<td>University of California, Los Angeles</td>
<td>2000-2001</td>
</tr>
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</table>
8.9 Media Publicity received by the Center

Provide in Appendix D any appropriate media materials that can be used to disseminate information on Center accomplishments and activities to the public.

Magazines:

• Discover Magazine in November 1999 featured a story about CfAO studies of Saturn’s moon Titan, using the Keck Telescope. The story is also on the web at http://www.discover.com/nov_99/breaktitan.html

• Adaptive optics images of Neptune obtained by CfAO researchers were featured as the cover story for the March 4, 2000 issue of Science News. The article was entitled “Getting a Clear View.”

• The Center’s work in adaptive optics was the cover story in Silicon Valley Tech Week, October 30, 2000.

• The Center and Center researchers were highlighted in an article in the Nov. 14, 2000 issue of Time Magazine. The article was entitled “Beyond Hubble.” It provided an explanation of adaptive optics technology, and highlighted the excellent visual quality of images obtained using AO on earth-based telescopes. Photographic images (obtained from CfAO) were used to demonstrate that adaptive optics image quality rivaled that obtained by Hubble.

• The February 2001 issue of SPIE’s OE Magazine featured an article about Center adaptive optics and laser guide star efforts at Lick and Keck Observatories.

• An article in the March 2001 issue of Popular Science entitled “Super Vision” featured Professor David Williams and the CfAO vision science group at the University of Rochester. The article described the use of adaptive optics to improve visual acuity and the advances likely to occur in both laser eye surgery and vision prescriptions for contact lens and spectacles.

• Astronomy Magazine featured adaptive optics images of Neptune obtained under a CfAO project.

• An upcoming issue of Sky and Telescope magazine will include a feature article about adaptive optics, including interviews with Center scientists.

• Natural History Magazine plans to feature the Center’s adaptive optics image of Uranus and its rings in an upcoming issue.
Radio and Television

Live in the Community Program, KZSC, July 16, 2001, 5:00-6:00 p.m. CfAO Stars, Sight and Science faculty instructor Professor Gene Switkes was interviewed along with a participating student, Stephanie Avila, from North Salinas High School. An audio cassette is available from the CfAO by request.

A local cable TV station in Santa Cruz is planning a one-hour special on adaptive optics featuring Center scientists.

Corinna Wu, a radio producer for the AAAS, visited the Center in June 2001 and interviewed Center faculty, post docs, and staff as part of a Science Magazine-affiliated radio program she is preparing on Adaptive Optics.

World Wide Web

Andrea Ghez’s use of the Keck telescope to detect a supermassive black hole lurking at the center of the Milky Way galaxy was featured on Passport To The Universe, a program enabling students across America to interact in real-time via the World Wide Web with some of the nation’s leading astronomers.

The CNN.com web site featured the Center’s adaptive optics images of Neptune – see http://www.cnn.com/2000/TECH/space/01/18/neptune.titan/

CNN.com’s standard image of Saturn’s moon Titan was obtained by CfAO scientists at the Keck Telescope. See :http://www.cnn.com/2000/TECH/space/08/23/moons.of.mystery/index.html

10. Appendices

Appendix A – Biographical information for new faculty member
No new faculty members
Appendix B1 – Organization Chart, Center for Adaptive Optics (Year 2)
Appendix B2 – Organization Chart, Center for Adaptive Optics (Year3)

* Highlighted boxes identify where changes have been made in the Organizational Chart relative to Year 1
Appendix C – Summary Minutes of Advisory Board Meetings

1. 2001 Report of the Program Advisory Committee
   Center for Adaptive Optics

   The Program Advisory Committee (PAC) submits this report to summarize our conclusions after meeting with several members of the Executive Committee of the Center for Adaptive Optics (CfAO) on May 18 and May 22, 2001. The PAC reviewed the new direction of the CfAO and assisted the CfAO in its review of proposals for Year 3. The persons who attended the two meetings were:

   May 18:   PAC:   James Beletic, Mark Colavita, Stanley Klein, Steve Vogt
             CfAO:   Jerry Nelson, Chris LeMaistre, Lisa Hunter, Claire Max, Scot Olivier, Austin Roorda

   May 22:   PAC:   Francisco Hernandez, Joyce Justus, James Beletic (by telephone)
             CfAO:   Lisa Hunter, Chris LeMaistre, Claire Max (by telephone)

   The full day meeting of May 18th reviewed all aspects of the CfAO, whereas the one-hour meeting on May 22nd concentrated on the EHR (Education and Human Resources) portion of the CfAO.

   General Comments

   The PAC fully endorses the revised direction of the CfAO. The four themes are very appropriate and working well. We like the layout of the new organization. We think the idea of “monuments” is a good approach and look forward to the CfAO coordinating the development of several pieces of hardware that are important to the future of AO: MEMS, sodium lasers, new 3-D retinal imaging techniques and AO phoropters and Fundus cameras. Less tangible but equally important are the advances that the CfAO is pursuing in the areas of point spread function (PSF) understanding and multi-conjugate AO design for extremely large telescopes. In parallel with the longer term developments, we support the effort that the CfAO is putting into making the existing AO systems work better and using them to demonstrate the scientific capabilities of AO.

   The CfAO is attempting to influence a very wide range of AO activities and a valid concern is whether the CfAO is attempting to achieve too much, putting too little resources into each of too many activities. However, after reviewing the programs that the CfAO will concentrate on in year 3, the PAC feels that the CfAO is finding a good compromise between reaching too far and influencing a broad range of AO developments. The CfAO unfortunately will not be able to pursue all of its desired activities in year 3, but instead will restrict its efforts in specific areas in order to provide
focus and concentrated resources in other areas. In order to be able to increase the amount of funding for retinal system development, the CfAO has needed to reduce the amount of funding for scientific application of AO and also to minimize resources for extreme AO. This is necessary in spite of the large amount of leveraging that the CfAO is able to achieve – e.g. MEMS development, sodium laser guide star development, MCAO and ELT design studies.

**Program Specific Comments**

The PAC spent a significant portion of the May 18th meeting discussing and rank ordering the proposals “on the margin”, i.e. those proposals for which the CfAO proposal review committee (PRC) needed independent assessment. Specific advice was given on several proposals. We feel that this time was well-utilized and our time was efficiently used, due to the good level of preparation by the CfAO and the PAC prior to the meeting. The PAC members all prepared for the meeting by reading the 50 proposals prior to the meeting.

With regard to the various areas of research, we have the following comments:

a) The laser development efforts are high-payoff, but also high risk. We recommend that the CfAO should provide oversight and regular review of these programs.

b) The 3-D optical coherence tomography instrument holds great promise, but the design needs to undergo a rigorous conceptual design review to assess its feasibility. Bringing in experts from the astronomical AO community as part of the review board would be a good example of center effectiveness.

c) The SETT program proposed by the Center, which will provide mentorship to underrepresented students at a critical juncture of their college studies, holds great promise, but we recommend that the Center proceed with only two nodes initially until more experience is gained with this innovative approach.

d) Although the Center has progressed from being a mini-NSF in its approach to soliciting proposals and awarding funds, there is further room for improvement in cohesion amongst Center members. This is evident in the number of redundant proposals for point spread function (PSF) characterization and computer simulation of AO systems. We discussed this at length with the CfAO Executive Committee and we all agree that the CfAO can effect more cohesion during year 3 by forming working groups in the following areas: (i) PSF characterization and deconvolution, (ii) computer simulation of AO systems, and (iii) design of AO systems. We strongly encourage the CfAO to carry through with this concept and ensure that it works by assigning responsibility to capable chairs and periodically reviewing the process.

e) The Center should be more pro-active in its placement of CfAO research news in the national media.

*Closing comments*
The PAC process was much better coordinated and prepared this year. We are witness to the maturation of the CfAO and we look forward to reviewing its continued progress.

Submitted May 25, 2001 by the CfAO Program Advisory Committee

James W. Beletic (chair) W.M. Keck Observatory
Mark Colavita Jet Propulsion Laboratory
Francisco Hernandez University of California, Santa Cruz
Joyce Justus University of California, Santa Cruz
Stanley Klein University of California, Berkeley
Steve Vogt University of California, Santa Cruz

Report of the External Advisory Board

19th July 2001

Executive Summary

The Center for Adaptive Optics has progressed very significantly over the past twelve months, in response to internal and external reviews. The CfAO has worked hard to achieve a clear budget process and now has a well-defined reporting relationship to the UCSC administration. It has also undertaken an extensive review of the scientific focus for the center. These absorbing activities, stimulated by the previous NSF site visit report, have been carried out with enthusiasm and good effect.

A recurrent element of this year’s EAB Review was the recognition that the management of the Center had made an excellent start to redefining the mode of operation. As the management itself stated on many occasions, they were aware that the process was not complete, and many of the detailed comments made in our report are already well-recognized by the Center. As a general rule, the EAB does not advocate further adjustments in the management processes of the Center until the recent changes have time to produce a significant track record.

The four new themes appear to the EAB to be well chosen and designed to have a significant and widely recognized impact on the development of adaptive optics and creating a “center culture”. There has been a systematic approach to identifying technologies that are common to both astronomy and vision science, and we see clear evidence for a much more collaborative and integrated program with the two communities working in much closer partnership. There remains the need to develop project timetables and milestones over a 5-10 year timescale, as we noted in last year’s report. This should be regarded as a priority.

Because of the issues raised at the NSF Site Visit, the June 2001 review focussed largely on management issues. At future reviews, the Advisory Board looks forward to hearing
about scientific progress. Encouraging a vigorous and highly visible scientific culture throughout all activities is essential to provide the scientific vision driving all the themes of the Center. A wider involvement of representatives of the institutions forming the Center in the EAB Review would also be beneficial.

Chris Dainty (Imperial College, London) (Chair)  
Thomas Jeys (MIT Lincoln Laboratory)  
Robert Kirshner (Harvard-Smithsonian Center for Astrophysics)  
Matt Mountain (Gemini Observatory)  
Maria Santos (Wallace Reader’s Digest Fund)  
Allan Wirth (Adaptive Optics Associates, Inc)  
Sidney Wolff (National Optical Astronomy Observatory)

**Introduction**

The second annual meeting of the External Advisory Board (EAB) was held on June 1st and 2nd in Santa Cruz. The presentations by the CfAO focussed largely on the management and related issues raised at the previous meeting of the EAB in June 2000 and at the NSF Site Visit in September 2000.

The CfAO has taken important steps toward establishing a vigorous and effective Center with a sound organization and well-defined practices. In the past 12 months, the Director, his Senior Staff and the Center membership have put in a tremendous amount of very positive work in focusing activities around four broad themes and building a “center culture”. The management team has been considerably strengthened with the addition of Chris Le Maistre as Managing Director and Lisa Hunter to lead the Education and Human Resources Theme.

It was clear throughout the Review that the Director, the Managing Director and the Theme leaders are working very well together, and through their collective action have effectively re-directed the Center’s core activities to be responsive to the previous EAB Report and to the NSF Site Visit Report. The Director and his management team are to be commended on accomplishing this task.

**Mission**

The newly developed mission statement defines 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 catalysing the advances nationwide with the next decade”.

The CfAO is surely a Center for Adaptive Optics, but it has not yet become the Center of US effort in this area. In astronomical AO, centers of activity at Gemini, the University of Arizona, and Hawaii are also significant. How can the CfAO increase its utility to this
science more broadly? One way is to facilitate the discussion of AO and its technical requirements among a broad range of scientists. The field of astronomical AO is young enough that a continuing discussion of alternate schemes for high-resolution imaging, as well as a broad discussion of wavefront sensing, deformable mirrors, analysis software, and many other topics needs to be facilitated. The CfAO can become the center of these efforts as well as a source of technical innovation by organizing sessions at specialized meetings, continuing to run a vigorous summer school, and organizing specialized workshops. One possible innovation might be a lecture series, presented by visitors to Santa Cruz, but webcast to all the CfAO sites (and beyond) especially from AO experts who are not now involved with the CfAO.

To further enrich its potential for success, the Center staff should consider who and what other organizations still need to be invited to participate in the Center or partner with it. This would take into account work in adaptive optics being done nationally and internationally. To strengthen its leadership in the field it should consider establishing a set of unique activities to facilitate knowledge transfer in each of its theme areas.

The CfAO has been heavily focussed toward astronomy in year 1 and is now focusing more resources into vision science. The technology of AO is very likely to have a major impact in the much more commercial areas of vision science and communications. The CfAO has acknowledged this possibility, and should start to develop plans that leverage the additional funding revenue that may become available with this expansion of AO into vision science.

1. Management Issues

1.1 Management Structure

The EAB welcomes the strengthening of Management through the appointment of Chris Le Maistre as Managing Director. We also welcome the streamlining of the Executive Committee, which now has a total of 11 persons (Director, Managing Director, 4 Theme Leaders, Site Coordinator Representative, 2 Technical Experts and 2 Science Experts).

Some members of the Center not present at the Review requested (by email) that the EAB consider the possibility that the Santa Cruz based Director report to an Inter-Institutional Deans’ Committee. The EAB do not recommend such a structure: it would diminish the role of the Director and might emphasize potential territorial conflicts that could weaken a Center with many nodes.

1.2 Timetable and Metrics

The CfAO has made significant progress in defining its role in the development of adaptive optics. The CfAO is now focused on four themes (Education and Human Resources, Adaptive Optics for Extremely Large Telescopes, Extreme Adaptive Optics,
and Vision Science Instrumentation). The most recent CfAO proposal review process was conducted to advance these themes and this has resulted in a change in the composition of funded proposals. The EAB is impressed with the speed with which the CfAO has reorganized itself in response to the PAC, EAB, and NSF reports.

While the new themes provide a way for the CfAO to establish important legacies in adaptive optics and to encourage a true “center mode” of operation, the next step will be to develop a detailed implementation plan, including a timetable with measurable milestones for the execution of the themes. The early development of a timetable with measurable milestones for each theme is critical to the management of the theme. Without such timetables it will be difficult for the CfAO, and nearly impossible for external reviewers, to assess the progress of the CfAO towards successful completion of the themes. As mentioned in the previous External Advisory Board report, the construction of these timetables and milestones will further focus the CfAO management and its members on the themes.

The milestones for each theme should be placed on a time line that illustrates the interrelation of the various tasks and the critical path for completion of the Theme. A well-considered timetable should extend for at least five years and a visionary timetable should extend through the end of NSF support for the CfAO. Updated timetables noting schedule slippages or priority changes for each Theme should be included in the CfAO Annual Reports and in presentations to the EAB.

The four themes represent a significant departure from the four goals set by the CfAO for the first two years of its operation. Specifically, emphasis has shifted away from support of individual science programs; in effect, during its first two years, the CfAO jump started a number of programs that produced important results (see the Annual Report) but that are now in a position to compete for more conventional grant funding. The CfAO has also elected to place much lower emphasis on the dissemination of AO tools and software to the community of AO. While this is a reasonable choice given the resources and personnel available to the CfAO, it is important that this work be carried out by someone. Adaptive optics cannot become a broadly useful scientific tool unless a systems approach is taken, from the building of the instruments to the reduction of the data. Even though the CfAO does not plan to undertake the dissemination of the necessary data reduction packages, it should encourage other groups to do so and make any information that it has about algorithms and techniques easily accessible to those who are prepared to develop user-friendly software packages.

1.3 Internal Review Process

The Center’s re-vamped review process seems extremely thorough and transparent. The process for reviewing funding proposals was well thought out and implemented in a way that gave proposers the information needed to respond to the new directions of the CfAO. In any situation where funding patterns and priorities change, however, there are likely to be questions raised about whether the process itself was fair. While we have no reason to question the process that was implemented this year, we suggest that in future the director
rely primarily on advice as to which proposals should be funded from a Committee that balances the needs of the Center with the need to be impartial. The membership of this Committee should include recognised experts who are external to the CfAO.

Having external experts playing a significant, but not necessarily dominant, role will help alleviate the perceptions of conflict-of-interest on the part of those making the recommendations, while ensuring the Committee is still responsive to the overall mission of the Center.

In the final analysis, decisions about funding must reside with the Director, who is responsible for making the difficult decisions that will determine the degree of success of the CfAO. The Director might in future reserve some discretionary funds that, in combination with the funding recommended by the external committee, would ensure a balanced and complete program. The primary factor in allocating funding should be relevance to the overall CfAO goals.

2. Thematic Issues

All the themes elaborated by the CfAO encapsulate ambitious goals for the Center. In each case, a careful statement of the scientific case is an essential way to assess whether the proposed technology is adequate to achieve the stated goal. At the time of our meeting, these science aims needed further definition. It is critical that science goals be established for each of the themes. These science goals can then be translated into performance goals and requirements for such systems as eXtreme AO. Successful programs depend on a clear definition of what is good enough.

1.4 Theme 1: Education and Human Resources

The Center for Adaptive Optics (CfAO) has made significant progress in Theme 1, in response to the issues and concerns raised by the External Advisory Board and NSF site visit. On the issues of cohesion in the education programs, the CfAO, under Lisa Hunter’s educational leadership, has developed a clear focus for its work in the area of public science education. Through meetings and retreats the members of the educational advisory have created bold and innovative education programs that add value. The Center has made a significant shift in its educational plan and its new cohesive plan hopes to:

- Bring CfAO research to the high school and community college community
- Increase the number of local underrepresented high school students who transition to college
- Increase the number of underrepresented undergraduate students who finish a four year program and advance to graduate school
- Increase the versatility of Center graduate students and post docs
- Increase the diversity of the Center
Five strategies new to CfAO members are being employed and supported by the Center to meet these goals. They are:

- The development of stronger internship programs
- Creation of cohesive mentorship programs
- A professional development program for graduate students and post docs
- Materials development
- Summer institutes for students and on site support for high school teachers

Outcomes of the work include:

- Mentoring models and knowledge sharing on effective mentoring strategies
- Inquiry models and instructional materials for CfAO research broadly used by scientists
- An effective model for the recruitment and retention of underrepresented students
- Increased numbers of scientists who work on educational issues and diversity

In CfAO’s most recent review of proposals the focus presented above was employed to select the set of third year grants. The shift in education from a collection of projects to a more focused plan is a step in the right direction. A challenge posed by the shift was the reduction of science education programs in the diverse nodes of the Center. This has come about due to the NSF requirement that emphasis be placed on innovation in science education, rather than on the funding of continuing programs, even if the latter are highly successful. We suggest that the Center consider ways in which to build the capacity of nodes with educational interest and expertise to compete successfully given the new direction.

The CfAO still needs to identify five and ten year milestones for the education goals that will provide a roadmap for their work. This will be helpful for monitoring progress, assessing effectiveness, setting metrics and enabling the capacity of center members to focus on meeting the goals. A clear roadmap will support the selection process for the portfolio of projects over the next seven years. In addition, it still might be useful to identify a set of physical ideas or concepts that would provide a focus inspired by the field of adaptive optics for CfAO materials development and inquiry based professional development.

The key strategies CfAO proposes to use over the next years need to have broad support among Center members. For example, the mentorship strategy might require more than 5% of the scientists’ time. As a more comprehensive method for mentoring is introduced and common strategies or tools are promoted, additional time for professional development and assessment will be needed. The new mentorship models proposed by the Center such as “paired mentoring” might challenge the current notions of mentorship. If this is a contribution of the Center then its impact needs to be measured. This again will require an increased level of participation from scientists.
The education unit of the Center held a conference for graduate and post doc students from the nodes. The conference engaged participants in inquiry and group-based learning, two areas of educational best practice. This traditional forum was used innovatively to create the first stages of community practice across nodes in CfAO educational and public outreach. This type of activity promises to create a community of scientists interested in educational issues and working together to create and share solutions to the many challenges that will arise as the CfAO strives to meet its education goals. This activity could become a central knowledge transfer activity for the education theme in addition to virtual forums.

The educational unit is integrating educational best practices in the strategic areas of the Center’s work. The Center staff is encouraged to sustain its current focus and build the capacity of a set of nodes to further this work and address diversity more fully. In addition to benefiting from the knowledge generated by the nodes of the Center we encourage staff to connect with other science and technology centers working on education and the NSF funded Centers for Science, Mathematics, Engineering and Technology Learning and Teaching.

1.5 Theme 2: Adaptive Optics for Extremely Large Telescopes

The adoption of this theme is a welcome and necessary component of the CfAO since this will be the focus of much of the AO development in groundbased astronomy over the next 5 – 10 years. In addition, the development of the techniques to deal with the tomographic calculations and data processing requirements may have future applications in wide field retinal scanning. The dilemma facing the CfAO is how to structure a leading program in the face of considerable external, and in some cases better-funded competition.

The Center’s current approach is to accrete the totality of expertise it needs to establish some form of leadership role centered on the needs of the 30m CELT telescope. Over the decade this may be an admirable goal, especially given the focus on a 30m groundbased telescope in which undoubtedly UCSC will have a central role. However over the next five years, given the fractious and competitive nature of the communities involved in adaptive optics both within the US (including at least one other CELT partner) and internationally, it is not clear this approach will both best serve the interests of the broader US community (which today is excluded from CELT) or will succeed.

The Center should consider assuming a more wide-reaching US leadership role in MCAO over the next decade. The whole MCAO endeavor, enabling wide field AO corrected fields on 30m – 100m telescopes is going to be a considerable undertaking for the entire global astronomical community. However despite the need to develop sophisticated model techniques, requiring collaborations with skilled mathematicians and supercomputing centers, the requirement for concerted coordinated activity to develop the necessary technologies such as lasers, large deformable mirrors, wavefront sensors and processors, little effective coordination between all the MCAO groups actually exists – even though this is in everyone’s mutual self interest.
Consequently, we would recommend that the Center, takes a broader, community based leadership role in developing a community based 10-year “road map” for the development of MCAO for 30m –100m class telescopes at least within the US and with some of its astronomical partners (Gemini, Canada etc).

The authority of the Center as leader of a community program can be securely based on its ability to articulate a coherent program for MCAO, its ability to effectively leverage the intellectual resources from the many diverse programs (ensuring the whole is greater than the sum of the individual parts) and by coordinating the procurement and delivery of the key technologies required to realize MCAO at the 30m scale.

For example, at present, it appears that laser guide stars are required for the successful implementation of astronomical adaptive optics over the vast majority of the sky. However, there does not now exist any laser system that has been demonstrated to be adequate for routine astronomical applications. Failure to develop an appropriate laser system may severely limit the promise of astronomical adaptive optics.

The present state of AO laser technology is a direct result of the lack of significant funding over the last decade for a diverse set of developers. Given the central nature of laser guide stars to the success of this CfAO Theme, the Center should try to establish a more aggressive program for the development of appropriate laser technology. Attracting the attention of competent laser developers (beyond the two presently supported by the CfAO) may require levels of funding which exceed the present resources of the CfAO. In this case, the CfAO should seek additional funding for laser technology development and leverage this funding with other interested organizations. If funding can be found, the CfAO should “advertise” its willingness to support laser development within the laser development community (e.g. laser AO session at the Conference on Lasers and Electro-Optics). Of course, the CfAO must not solely focus on laser development but on all aspects of AO.

By initially assuming a role “catalyzing advances nationwide with the next decade” [CfAO Mission Statement], the Center’s stature will grow into a real leadership position, comparable to or exceeding the EU and ESO funded activities in Europe. As a consequence, this in addition should result with CfAO becoming the focus and natural accretion point for the communities MCAO talent and hence the natural (and undisputed) leader for 30m class AO systems.

1.6 Theme 3: Extreme Adaptive Optics

The CfAO should be commended on adopting this as a major Theme. Achieving diffraction-limited performance at optical wavelengths in particular will be a challenging and exciting capability for modern groundbased astronomy and a good vehicle for the development of new and critical adaptive optics technologies and techniques. For example, achieving this performance even on a 3m – 4m telescope will require kilo-
actuator adaptive mirrors, and on 8m – 10m telescopes adaptive mirror technologies will have to be pushed to the $10^4$ actuator regime, well beyond the limits of current technological and computational approaches.

In addition the “Extreme AO Theme”, will challenge our current theoretical modelling of the turbulence physics of the atmosphere, pushing modellers to look beyond the current approximations inherent in the generally accepted “sum of the phase screens” approach. In addition, the whole role of atmospheric scintillation in adaptive optics correction using just a single deformable mirror will have to be extensively investigated. Ultimately pursuing a more rigorous analysis and modelling approach to these issues should lead to a better theoretical understanding of the propagation of light through a turbulent atmosphere and can only enhance our ability to build AO systems for the next generation of 30m – 100m telescopes.

This theme has a better-defined program than Theme 2 and the development goals are achievable. In addition this Theme shows clear interdisciplinary synergies with vision science. However the astronomical science drivers need to be emphasized more and the EAB would strongly recommend that as a priority, this Theme establish and articulate a strong science case for extreme AO on 8m-10m class telescopes. We believe this will be essential to enable this Theme to establish realistic, and hence realizable limits to the necessary theoretical and technological developments required for a real 8m-10m telescope system.

The technical and modelling requirements for this work should then be derived from the scientific goals. This is the only way to know how “good” is “good enough”. The archetype problem of imaging a Jupiter in a Sun-like planetary system could be used to develop a set of technical requirements. Based on the above requirements definition, the road map should be converted into a real schedule with milestones in the very near term.

1.7 Theme 4: Compact Vision Science Instrumentation

The optical system of a normal human eye is not perfect, at least over the whole range of possible pupil diameters. In addition, a large percentage of the population use some form of correction for focus and astigmatism such as spectacles, contact lenses or refractive correction via laser treatment. Adaptive optics offers the possibility to correct the aberrations of the eye, with two key consequences: (a) individuals can be given visual acuity exceeding 20:20 (perhaps up to 20:10 or better) and (b) diffraction-limited images of the retina, with an angular resolution on the order of 1-2µm, can be obtained. In addition, there is significant future potential for one component of an AO system, the wavefront sensor, to be used as a diagnostic and measurement tool, for example to make laser refractive surgery more effective. There is considerable commercial interest in this latter topic at present.

The Thematic programme presented to the EAB was relatively detailed, and in particular gave a broad time-line and key milestones and monuments. The interactions between
the vision and astronomy themes were detailed, and the areas which were highly leveraged had been identified. The major “meta-goals” were clearly identified, addressing a concern raised in the NSF Site Visit report. This Theme includes the key groups in the US, and during the past year a number of new groups (at UCD, UCSD, UCB and John Hopkins) had been added, addressing the other issue raised by the NSF Site Visit report.

The members of the CfAO involved in this area are well-connected to the ophthalmic instrumentation industry and are aware that wavefront sensing and adaptive optics are rapidly developing in the commercial sector. This is the most promising area within the CfAO’s portfolio that is likely to lead to commercial exploitation. The IP issue has been clearly defined by the Center, i.e. the IP is held by the individual universities at which the PIs reside, not by the CfAO: this policy is straightforward but could lead to legal wrangling in the future since CfAO projects are inherently collaborative in nature and obtaining agreement between institutions on ownership may prove difficult.

Of the three technical themes, this has the most concrete plan with reasonably well defined “monuments” and schedule. If this can be made into a schedule with the next level of tasks defined, they will be ready to achieve good, verifiable progress. One concern is that this theme is competing in a hot commercial area. They need to make sure they keep on top of developments in this area or they risk being left behind. The schedule that was presented is not as aggressive as some commercial projects. This is also an area where more involvement of outside workers is critical. The CfAO has anticipated this and will engage additional corporate partners with expertise in ophthalmic instrument design to aid the commercialization effort. This theme is also one in which the issue of IP and proprietary developments will play a big role.

3. Other Recommendations

1.8 Global Links

The Center’s goal to establish leadership nationally in adaptive optics could be significantly enhanced if it were to play a more pro-active role internationally, perhaps taking the lead by forming alliances with key groups outside the US, for example with the European Southern Observatory and vision science groups in Europe and elsewhere. One way to promote the international perspective would be to sponsor international workshops in astronomical AO and AO for vision science (for example, like the May 2001 Venice and November 2000 Murcia meetings respectively).

1.9 Communications

The CfAO is urged to continue its consideration of internet-II based video conferencing to assist communications within the Center.
1.10 Intellectual Property
The intellectual property issue is being systematically examined and clarified by each institution. The policy of the CfAO regarding IP is logical but may be too simplistic in view of the likely expansion of commercial interest in AO. By leaving the IP arrangements to member institutions, the CfAO cannot present a Center based policy to interested industrial partners. We understand that this issue has been discussed at length at a meeting of the Executive Committee of the CfAO on July 11, and that good arguments have been presented for retaining the present policy.

1.11 Composition of the EAB
The External Advisory Board would be strengthened by the addition of one additional person from the US whose experience was in the area of mainstream vision science. This would provide an improved balance of expertise on the EAB, bearing in mind that the present 1.5 persons with vision science expertise (Artal and Dainty) are resident in Europe.

1.12 EAB Business:
The presentations to the EAB in June 2001 emphasized the new organizational aspects of the CfAO and largely involved staff local to UCSC (and LLNL). A regular part of every EAB presentation should also include a summary of scientific highlights and a measure of the Center's progress against its long-range plan and intermediate milestones. A clear statement of the program for the coming year, with explanation of the changes from the past and the connection to the future should be routine. This should involve CfAO members from as many as the nodes as practically feasible, both in the documentation and in the review meeting. If the timing of the EAB meeting needs to be changed to allow a presentation of the program's plan for the coming year, then the EAB will be glad to oblige.
Appendix D – Additional Media Materials

The following have been forwarded to NSF under separate cover:

1) CfAO Brochure: Developed as an aid to recruiting students into CfAO programs at member institutions. Used at meetings of the National Society of Black Physicists and of the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS).

2) CfAO Newsletter: Describes research and education activities of the Center. The first issue contained a feature article on the Center’s ALU LIKE Traineeship program, which brings Native Hawaiian interns to CfAO member institutions and then arranges follow-up positions at the various observatories and high-tech firms in Hawaii.


On the following page are two photos and a brief description of the CfAO’s “Stars, Sight, and Science” program held at UCSC this summer (July 2001).
Appendix D

“Stars, Sight, and Science” Program

Stars, Sight and Science students learn about light at a session on “Table Top Optics.” The four-week summer immersion experience included three coordinated courses on vision science, astronomy, and science communication developed by CfAO: The summer session is offered in conjunction with the California State Summer School for Mathematics and Science (COSMOS) program at UCSC.