Table of Contents

1. Executive Summary

1.1 Adaptive Optics and its potential

In many endeavors, ranging from our personal lives to the most advanced scientific research, there is benefit to be gained from better angular resolution – the ability to see finer detail - whether one is reading a newspaper or measuring structure in a distant galaxy: From better angular resolution more information about the object of study can be derived. Frequently the optical system that delivers the image is imperfect in some way and the angular resolution is degraded, thus preventing the system from reaching its theoretical maximum resolution, which is limited only by diffraction.

In a broad sense, Adaptive Optics (AO) seeks to measure and correct the optical imperfections that affect image quality, thus allowing diffraction limited resolution. Often these disturbances or aberrations are changing rapidly with time, so that the correction must also be dynamic. This is emphatically the case in astronomy, where one observes through the Earth's turbulent atmosphere. In other situations part or all of the aberrations are static for long periods, but their magnitude and form is unknown a priori. This is substantially true for human vision, which raises the possibility of improving human sight using techniques derived from adaptive optics, while dynamic AO technology allows us to study living human retinas at unprecedented levels of detail.

1.2 The Mission of the Center for Adaptive Optics

We seek to play a leading role in developing AO and expanding it's usage into a diverse set of applications where it can be of benefit. In spite of its power and importance, AO is not widely used today, for several reasons:

- It is technically complex, and sufficiently advanced methods of application do not yet exist – current AO systems are bulky and expensive.
- It has only recently been developed and its potential is not well known to scientists or engineers.
- because of its complexity, the skills needed to apply it adequately are not widely distributed, and many scientists lack the skills needed to apply it successfully to their situation.

The CfAO seeks to alleviate these deficiencies and bring AO into widespread use.

1.3 Goals of the Center for Adaptive Optics

Adaptive Optics was originally proposed in the 1950's for improving astronomical imaging, but only in the last decades has the technology improved sufficiently to make such applications possible. Currently AO systems are available on a only a few telescopes. In the field of vision science, AO is just beginning to be used, and it offers a powerful tool for greatly improving our ability to study the living retina in people and perhaps for improving human vision. These two topics, astronomy and vision science, form the core emphasis of the CfAO, although we hope to expand its use into other fields including optical communication.

Goal 1: Carry out forefront science with AO: The first goal of CfAO is to carry out exciting new science based on the use of AO. By doing so, we will demonstrate this technique's power and raise interest in furthering its acceptance and use. Equally important, it is only by using AO systems for science that we can determine their limitations and be able to guide the development of more powerful AO systems, instruments, and software tools.

Goal 2: Bring adaptive optics to the broad community: The second goal of CfAO is to support the wider use of AO by the scientific community – disseminating the knowledge currently known to a handful of AO experts. In practice this means we will provide tutorials in AO principles and usage, suggest effective techniques for its use, and produce software tools to assist in the planning, use, and data reduction of AO based observations.

Goal 3: Design and build instrumentation optimized for use with AO: The third goal of CfAO is to encourage and support the development of scientific instruments optimized for use with AO. Because AO delivers much improved image quality, and images of much smaller spatial extent, traditional instruments in astronomy and in vision science are poorly matched to AO applications. Thus, new instruments need to be developed to effectively use AO. We are supporting the operation of existing instruments, the design of new instruments for astronomy, and the construction of next-generation vision science instruments capable of AO-corrected 3-dimensional imaging of the retina.

Goal 4: Develop technology for advanced AO systems: The fourth goal of CfAO is to improve adaptive optics by pursuing the advanced technologies that will enable the next generation of AO systems to be more powerful, more versatile, and/or less expensive than the current one. Key technologies range from powerful lasers to make artificial stellar beacons for astronomy, to spatial light modulators as capable of correcting optical distortions as the current deformable mirrors but far more compact; such device could be of great benefit to spread the use of AO into vision science and ophthalmic applications.

Goal 5: Education and outreach: The fifth goal of CfAO is to effectively promulgate science oriented subjects into the fields of Education and Public Outreach. This ranges from bringing an excitement about learning, science, and optics to primary school children, to career advice for graduate students and post-doctoral fellows. Our outreach activities are quite diverse, partially because of our many and varied Center sites. We have taken advantage of existing EPO activities at these sites where we see a good match between the science and optics thrust of our Center and the EPO activity. We have also chosen to have individual Center members contribute a fraction of their time (typically 5%) to EPO activities. Challenges include finding unifying principles for the diverse EPO activities, and understanding how to make objective evaluations as to their effectiveness.

The use of adaptive optics in astronomy is better established than in vision science. We believe that applications in vision science have enormous potential, both for their scientific merit, and for the potential benefit to people in general. The Center has committed to spending 25% of its resources in supporting vision science AO. Even more importantly, we are bringing together the fledgling vision science adaptive optics community with leading groups in astronomical AO, thus facilitating transfer of skills resulting from two decades of military and civilian AO systems development into this emerging field.

1.4 Plans and structure of the CfAO

To effectively carry out the diverse objectives of our Center, we have, of necessity, created a center with many researchers distributed over a geographically widespread area. This is especially challenging for us, as to achieve our objectives we need to maintain strong interactions between these distance separated groups of researchers.

We have organized our research first into goals, as mentioned above. Each goal has an associate director, with special responsibility to the health of that goal. Then, within each goal, we have projects. Each project has a principal investigator who is responsible for the research of that project. There are some 40 projects all together. Many projects are collaborative, with work shared between multiple institutions.

In addition to the direct research projects, we have emphasized frequent specialized workshops for both members and non-members, and retreats for Center members.

1.5 Management

To achieve the objectives of the Center, We must develop tools to evaluate our work and to encourage new and exciting ideas, while weeding out the less promising ones and tapering off support for those activities that have already achieved most of their objectives. This work is being implemented at several levels.

The Center has an executive committee consisting of the Director, Managing Director, Associate Directors, and Site Coordinators (a lead representative from each University). The executive committee meets bi-weekly by telecon to discuss the more routine aspects of Center management. There are also person to person meetings to discuss more complex issues as the need arises. The EC has a major responsibility to encourage new projects and judge the value of existing ones.

Each project is submitted with specific, testable milestones that allow us to judge its planned progress. Brief monthly reports are required. The intention is that projects failing to meet milestones can then be identified, and suitable corrective and/or supportive action can be taken in a timely fashion.

Each project has a given budget, assigned annually, and expenditure reports are required monthly, along with the brief monthly progress reports. In the first year of existence this monthly reporting has been valuable, as it has clearly identified the challenges being faced in ramping up a large research activity. Generally projects have underspent against their budget because of delays in recruiting qualified postdoctoral researchers and selecting graduate students. This knowledge has aided us in planning for year 2.

The process of planning and budgeting provides the tools for shaping the research agenda of the Center, and in particular, eliminating projects that are weak or have completed their objectives, and introducing new ones. Because the Center has just started and projects are still in the process of ramping up, it is difficult to assess their effectiveness. Thus, in laying out year 2 activities we have made only modest changes from our original plan. However, a year from now we will have much additional information to guide us in making these assessments and changes where necessary.

1.6 Knowledge exchange

Many aspects of our Center activities involve the fields of commerce as well as other scientific institutions. We have partnerships with several research institutions and commercial firms with interests in adaptive optics and adaptive optics components. We believe these partnerships are of mutual importance and benefit. Our scientific research partners usually share an interest in AO systems in their entirety, while our commercial partners are more likely to be interested or expert in some specific component or section of an AO system. The potential in the field of vision science is particularly interesting, as there are several commercial possibilities, ranging from better ophthalmic instruments to contact lenses developed for supernormal vision. Our Associate Director for Knowledge Exchange works closely with the Center members at these partner institutions and companies. Establishing this network is a crucial part of transferring AO technology from astronomy into a broad range of other applications.

1.7 Summary

Though our Center is still in its infancy, we are tremendously excited by what we have learned in our projects so far, both in fascinating images in astronomy and in various recent studies in vision science. We have made unprecedented images of planets, imaged distant galaxies, resolved myriad stars near the center of the galaxy to study its black hole, detected candidate planets around other stars, and many other exciting astronomical discoveries. In vision science, we have begun large scale studies of optical aberrations in the general population, measured the waveguide properties of individual cones, and begun the developments that will lead to next-generation vision AO systems for broader use. Tools for using AO effectively are being developed. The designs for instruments for future AO are proceeding very well. A number of vigorous programs on different aspects of the technology needed for advanced AO are underway. Our future looks very bright and sharp.

Just as exciting as the scientific and technical progress, the Center member are getting to know each other and benefit from our collective knowledge and skills to the advantage of our entire Center effort. We are now strongly interacting with our partner institutions furthering knowledge exchange through workshops and other meetings.

The education outreach program is off to a good start as we collaborated with existing programs at the CfAO sites increasing their impact on their targeted groups. In the near future, the Associate Director for EPO programs position will be filled. This and the Center Education Outreach workshop to be held in the fall will result in the setting of goals and a consolidation of programs to align with these goals.

Our Center is blossoming, and we are looking forward to our second year of operations, with its challenges and exciting new discoveries and partnerships.

2.1: Goal 1: Science With Adaptive Optics

2.1.1: Vision science

Faculty: David Williams* (U. Rochester), Austin Roorda* (U. Houston); Don Miller* (Indiana U.)
Research Scientists: Geun-Young Yoon, Antonio Guirao, (U. Rochester) Fernando Romero (U. Houston), Richard Paxman, Kurt Kleichman (ERIM) Scott Olivier (LLNL); Ian Cox, (Bausch and Lomb), Larry Thibos, Arthur Bradley (Indiana U.), Eriko Miyahara, (RIT)
Staff: Ben Singer, Ted Twietmeyer, Barb Arnold, Teresa Williams, Debra Haskins, (U. Rochester), Xiaofeng Qi (Indiana U.); Marilyn Levi, Chris Keuther, Hope Queener, (U Houston.)
Postdoctoral Fellows: Li Chen, Nathan Doble, Yasuki Yamauchi, (U. Rochester); David Lande, (LLNL); Jiyuan Liu, Huawei Zhao, (Indiana U.)
Graduate Students: Heidi Hofer, Aris Pallikaris, Jason Porter (U. Rochester); Fan Zhou, (Indiana U.); William J. Donnelly, Chiyu Liu, (U. Houston) Shannon Maloney, (U. Rochester); Brent Wilson, (U Houston)
* indicates PI of a Center Project in this Goal.

The new frontier for adaptive optics is in the field of vision science. Presently, the Rochester AO ophthalmoscope is the only system in the world that successfully uses adaptive optics for correcting high order aberrations in the eye. To expand and develop the field, the Center for Adaptive Optics funds three sites which are solely devoted to developing adaptive optics for vision science: groups at the University of Rochester, Indiana University and the University of Houston. The vision science groups collaborate and consult with the astronomical AO groups that have much longer experience in AO system operation, a relationship that has contributed to the rapid progress towards the Rochester 2nd generation AO system. In addition, the CFAO funds development of next-generation AO technology that will be useful to both vision science and astronomy; discussed in section 2.4.

The University of Rochester is developing a new AO system that improves on their current design, while Indiana University and the University of Houston are each applying AO to alternate imaging modalities, that will be used image the retina in three dimensions. This is discussed in more detail in section 2.3.2. Close collaboration ensures that technology and ideas will be shared between the sites. Research done with these instruments will establish the requirements for building smaller, less expensive AO devices for vision science, and will also expand the possibilities for basic vision science and clinical ophthalmic applications.

2.1.1.1 Real-time adaptive optics system for the human eye and the second-generation Rochester AO system. (PI: Williams)

The aberrations of the eye are dynamic, requiring an AO system with a closed loop bandwidth of about 1-2 Hz to correct the important temporal variations in image quality. The original Rochester vision science AO system was incapable of keeping up with these dynamic aberrations, requiring the use of drugs to slow the fluctuations in subject eyes. By upgrading the real-time components of the current system, Rochester investigators have now demonstrated the first closed loop AO system ever built for the human eye. The wave aberration measured at 21 Hertz during active compensation decreased the average residual rms wave front by about a factor of two compared with static compensation and resulted in superior retinal imagery and reduced requirements for drugs.

The design of Rochester's second generation AO system for the eye has been completed. The new system will incorporate a 97 channel PMN actuator deformable mirror replacing the current 37 actuator DM. The new layout will allow efficient insertion of alternative deformable mirrors in the system, such as the spatial light modulator under development in collaboration with LLNL.

During Year 2 the system will be constructed. The Gen 2 system at Rochester will incorporate optics that allow wavefront sensing and retinal image acquisition to occur simultaneously, which is not possible with the generation 1 device. The new design will also add an automated focussing mechanism for the science camera, to correct for the chromatic aberration of the eye and the fact that the wave front sensor and the science camera operate at different wavelengths.

Once the Rochester Gen 2 system is completed, we will conduct experiments on human eyes to determine how quality of correction varies with the rate of operation of the AO system. Tests of closed loop performance will include the resolution of images of the retina and the contrast sensitivity of the eye viewing visual stimuli through the AO system. One goal is to be the first to resolve the tiny rod photoreceptors in the living human eye.

2.1.1.2 Design of an optimized vision-science AO system (PI: Miller)

The design of an optimized adaptive optics system for the human eye requires a complete description of the eye's aberrations. Such data are also required to design customized contact lenses and laser refractive surgical methods that can correct higher order aberrations in individual eyes. A collaborative effort by Bausch and Lomb and the University of Rochester resulted in wave aberration measurements of 113 subjects. Calculations based on these data show that most of the population has significant high-order aberrations in addition to defocus and astigmatism, the latter being the only aberrations corrected with spectacles.

Wavefront correctors have not yet provided fully diffraction-limited imaging through the eye's ocular media. AO optimization is required for the development of less expensive and smaller devices, essential for the widespread introduction of ophthalmic instruments equipped with adaptive optics. Two of the goal 3 programs are working to optimize future AO systems and develop new instruments to take full advantage of the corrected images. They have modeled the performance of various configurations of piston segmented correctors in conjunction with measured wave aberration data of normal human eyes. The model included the effects of pupil size, mono- and poly-chromatic light, and also the actuator number, arrangement, and fill-factor. Results predict that diffraction-limited performance should be attainable for medium-sized pupils with existing, commercial wavefront correctors such as liquid crystal spatial light modulators. Large pupils – such as at the maximum physiological size of 8 mm – are expected to require several thousand degrees of freedom (e.g. an 8 mm pupil is predicted to require a 100x100 piston-segmented array).

The above modeling, however, was limited by the substantial computer time required to simulate the wavefront propagation through the corrector and eye, particularly when applied to many eyes and corrector configurations (e.g. number of actuators). In addition, it shed little information on the underlying optical behavior of the eye that dictates corrector performance. The analogous situation in astronomy would be using a full simulation of the turbulent atmosphere to predict imaging performance, rather than the well-developed Kolmogorov scaling laws and Fried relationships. To avoid these limitations, we are currently seeking an analytic solution for predicting the performance of other types of wavefront correctors. The analytic solution will require a statistical model of the wave aberrations — namely the phase structure function — for a population of normal eyes. Because the structure function is not known for the eye, we have begun to empirically determine its form from wavefront data we have collected earlier this year on 200 eyes at Indiana University. Preliminary results of the eye's phase structure function and its application to predicting corrector performance is planned for presentation at the Annual Optical Society Meeting in October of 2000.

The University of Rochester group has studied the other aspect of the problem – the wavefront sensor and needed number of subapertures. In addition, the group has computed how the correction afforded by a deformable mirror declines with decentration of the eye relative to the mirror.

2.1.1.3 Measurements of the increase in visual contrast sensitivity when corrected with adaptive optics.

Geun-Young Yoon at U. Rochester has made measurements of the visual benefit of correcting higher order aberrations in the eye with adaptive optics. This was done by testing the visual performance of subjects whose optical aberrations have been corrected with adaptive optics. These measurements are crucial for defining the benefits that can be expected from customized laser refractive surgery and customized contact lenses, as well as AO systems for the eye. By actually testing the vision of human subjects we can see to what extent the retinal and neurological structure limits performance once the aberrations have been corrected.

2.1.1.4 Fiber optics properties of single cone photoreceptors (PI: Roorda)

A collaboration between Rochester and Houston has produced the first direct measurements of the wave guide properties of single photoreceptors in the human retina – the variations in photoreceptor sensitivity to light entering at different angles. The long, fiber-like structure of cone photoreceptors give rise to waveguiding properties. These waveguides tend to orient themselves to preferentially receive light from the eye's pupil. Adaptive optics has allowed us, for the first time, to measure the waveguiding properties of individual cones. This is done by measuring the amount of reflected light from each cone as a function of the illuminating beam angle.

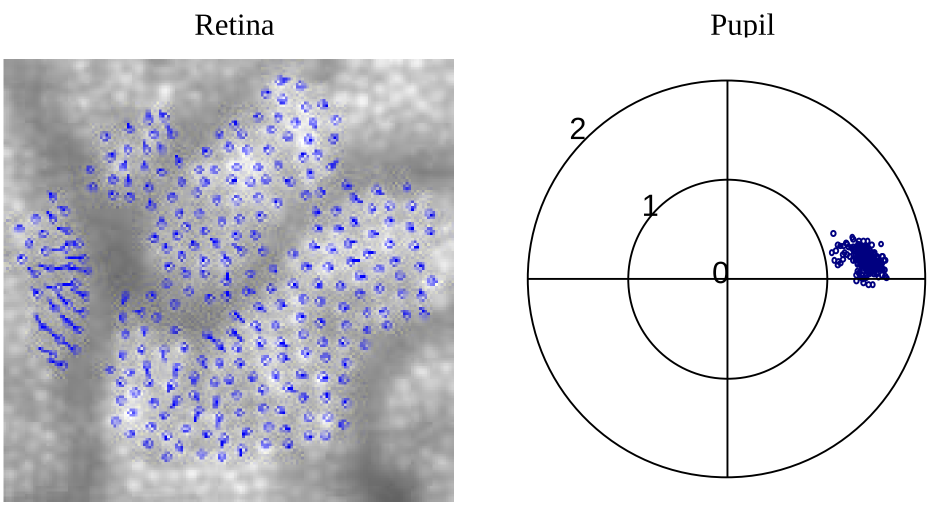


Figure 1: Waveguide properties of photoreceptors. The figure on the left is an image of the cone photoreceptor mosaic of a living eye. The blue circles represent the subset cones that were analyzed in the experiment. The lines in each circle indicate the angle and pointing direction of each individual cone. Each dot on the right figure shows the axis of each cone projected into the pupil plane of the eye (a 4 mm pupil is shown). Although we can detect systematic disarray in the ensemble of cones, the important conclusion is that all cone photoreceptors tend to point in the same direction.

2.1.1.5 Phase diversity as a method to obtain the refractive state of the eye and high resolution fundus images (PI: Paxman)

Phase diversity algorithms attempt to simultaneously recover a complex object and the aberrations disorting that object through use of two images taken at different focus positions. Rochester researchers are constructing a retinal imaging system that can take two pictures simultaneously in slightly different images planes, for enhancement with phase diversity. Rick Paxman, at ERIM, has processed retinal image pairs from the Rochester AO system and has demonstrated that phase diversity can produce substantial enhancement in retinal images. Phase diversity techniques, have been extensively used in astronomy but may be even better suited to the static aberrations of the human eye.

2.1.1.6 Low cost spatial light modulator for wave front compensation (PI: Williams)

A key CfAO goal is to develop low cost adaptive optics, since cost is a major impediment to the widespread use of this technology both in astronomy and in vision science. In Year 2, in collaboration with LLNL, Rochester will test a liquid crystal spatial light modulator (SLM) developed by Hamamatsu (SLMM X7550). A key feature of this device is that it is not pixilated so that diffraction by individual pixels can be avoided. Moreover, it has a resolution of 644 by 484, far higher than a conventional DM so that very high order aberrations can be corrected. Its size is small (1 inch) which is valuable in a compact, commercial instrument for a physician's office. Because the device is based on LCD technology, it can be made cheaply in large numbers compared with conventional monolithic mirrors. Although SLMs have limitations (polarization and chromatic effects) compared to mirrors, they have some of the capabilities of the MEMS technology (see section 2.4 and 4.2) under development, and, for vision science, provide a bridge between monolithic deformable mirrors and MEMS.

2.1.1 Astronomical Science

Faculty/Senior Researchers: Mike Brown* (CIT), Imke de Pater* (UC Berkeley), Sandra Faber (UCSC), Andrea Ghez* (UCLA), Raja Guhathakurta (UCSC), David Koo (UCSC)*, Shri Kulkarni* (CIT), James Larkin* (UCLA), Claire Max (LLNL), Scot Olivier (LLNL), Andreas Quirrenbach (UCSD), Arthur Wolfe* (UCSD)

Research Scientists: Don Gavel (LLNL), Seran Gibbard (LLNL), Vesa Junkkarinen (UCSD), Bruce Macintosh (LLNL)*, Drew Phillips (UCSC)

Postdoctoral Researchers: Gaspard Duchene, Franck Marchis (UC Berkeley), Matthew Britton (CIT), Antony Bocalletti (CIT), Eric Gawiser (UCSD), Karl Gebhardt (UCSC), Myungshin Im(UCSC), Jean-Luc Margot (CIT), Eduardo Martin (CIT), Jennifer Patience (LLNL), Eric Steinbringer (UCSC), Christopher Willmer (UCSC)

Students: Antonin Bouchez (CIT), Tiffany Glassman (UCLA), Suvi Gezari (UCLA), Denise Kaisler (UCLA), Ben Lane (CIT), Shuleen Martin (UC Berkeley), Caer McCabe (UCLA), Stuart Norton, Jennifer Roberts (UCSD), Henry Roe (UC Berkeley), David Sand (UCLA), Angelle Tanner (UCLA)

* indicates PI of a Center Project in this Goal.

The CfAO is currently supporting a number of astronomical science projects that were chosen for broad scientific interest and because they push the development of adaptive optics in ways relevant to the other goals of the Center. Initially, the benefits of these programs to the Center include the production of useful observational and analysis tools (see Goal #2 below) and input into the Center's education and outreach activities (see Section 3). In the first two years, this goal has been divided into three meta-projects that push different aspects of current AO systems' performance. It is expected that in future years, the emphasis of this Goal will evolve in parallel with the development of various AO systems and instruments (Goal #3 and #4.) Below we describe the highlights of the work carried out in year 1 and the overall plans for year 2.

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

Although radial-velocity techniques (Marcy et al) have discovered several dozen planetary companions to stars, these indirect detections are sensitive only to stellar systems very different than our own – systems with giant planetary companions in close orbits. Adaptive optics opens up the possibility of detecting systems which, like our own, have their most massive members in the outer part of their stellar system, by directly seeing the infrared light emitted by young or massive planets. Center members are carrying out surveys to find low-mass companions, brown dwarfs or even planets, around nearby stars and young stars.

A number of new low mass companions have been discovered in both studies. In the nearby star study (PI: Kulkarni) a 0.06" brown dwarf binary pair has been discovered, with an orbital period short enough to soon lead to a definitive mass determination for the pair – the first direct measurement of the mass of a sub-stellar object, critical for the calibration of the lower mass range of the evolutionary tracks.

In the young star (PI: Macintosh) study much lower mass companions, in principle, can be identified. The most dramatic case of a *candidate* planetary mass companions to a young (10 MYr) star is shown in Figure 2.

Analysis of the Keck data is ongoing to determine if this is a true planetary companion or a background star. In either case, this demonstrates that Keck AO has the sensitivity needed to see Jupiter-mass companions in 50-150 AU orbits around young stars. In Year 2, the goals are to (1) demonstrate that the low mass companions discovered through imaging are true companions through follow-up proper motion studies, multi-color observations, and spectroscopic measurements were possible and (2) extend the survey to a complete sample of bright young stars in nearby associations (TW Hydra) and younger regions (Taurus and Ophiucus).

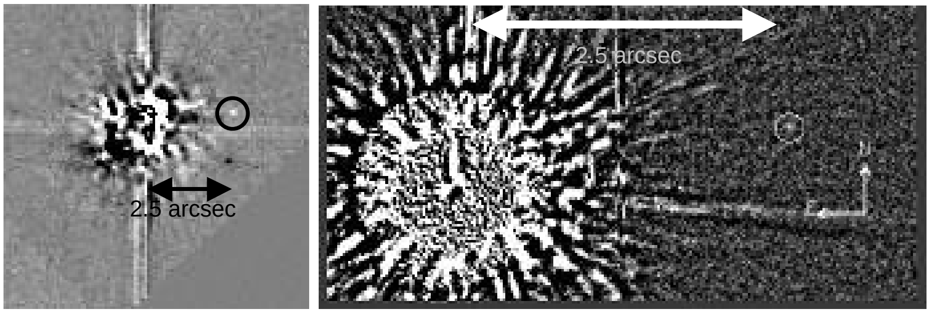


Figure 2: Candidate planetary companion. Originally detected by HST/NICMOS (left) in a 20 minute exposure, this companion is 10^5 times dimmer than its parent star, consistent with a 10 million year old 1-2 Jupiter mass planet shining from residual heat of formation. The companion was re-observed using the Keck AO system (right, 240 sec exposure.)

AO detection of the diffuse emission from circumstellar disks (PI: Ghez) is an exceptionally challenging problem. In the studies of disk material around young stars and main-sequence stars the year 1 focus was on developing optimal observing strategies, and working with other center groups on point spread function (PSF) characterization. Test data obtained by Center scientists led to a detailed characterization of the high-contrast structure in the Keck PSF (see Goal 2 below for more details.) This led to the discovery that the light is scattered by aberrations in the primary mirror, which in turn led to an improved observing strategy: by operating in a mode which keeps the pupil fixed with respect to the AO system the PSF structure due to both the AO system and the primary mirror remain fixed, thereby increasing the resulting dynamic range by about 1 magnitude. This observing strategy was adopted by the LLNL group carrying out the young plant search described above, who successfully detected the candidate companion object shown in Figure 2. Year 2 will focus on observational strategies for the detection of extended disks.

2.1.2.2 Extragalactic Adaptive Optics

The ultimate goal of this scientific program is to study the morphology, metallicity and star formation rates of faint galaxies as a function of age in the early Universe, and thereby determine when and how galaxies such as our own Milky Way formed. (PIs: Koo, Larkin, Wolfe). The preliminary images obtained in year 1 demonstrate the capability of AO to work on faint objects (see Figure 3) and are already indicating that galaxies may have significant infrared luminosity evolution even at redshifts less than one. Year 2's goals are to increase the number of galaxies imaged from 6 to a statistical significant number (~30) and to begin follow-up spectroscopic observations to study the galaxies' spectral properties, in particular to look

Figure 3: An AO image of a galaxy seen at the epoch of the formation of the solar system. This galaxy (near the star PPM 114182) has a large disk but a central unresolved core - a small bulge or perhaps a central active nucleus or starburst. There is also a point source located 0.6 arcseconds south of the nucleus which is most likely a giant star-forming region within the disk.

for the presence of active galactic nuclei.

2.1.2.3 Crowded Field Imaging – Stellar Clusters

Studying the Galactic Center (PI: Ghez) addresses two technical challenges of observing with AO – operating with dim, off-axis guide stars and carrying out photometric, astrometric, and spectroscopic analysis in a crowded field – as well as providing the best-ever information on conditions in the center of our galaxy, particularly the massive black hole located there. In year 1, we have demonstrated that both the Keck and (just as this is being written) Gemini AO systems are capable of observing the Galactic Center. A complete analysis of the Keck AO performance was completed and was used to help define the Science Case unique to the Gemini program, defining the complementary abilities of the two systems. The most recent set of Keck images have discovered a source that has flared near the position of Sgr A*, the putative supermassive black hole. In year 2, the focus will shift from imaging to spectroscopy of the sources in the central 1 arcsec^2 in order to determine their spectral types and radial velocities, leading to a three-dimensional solution for the orbits of stars around the black hole.

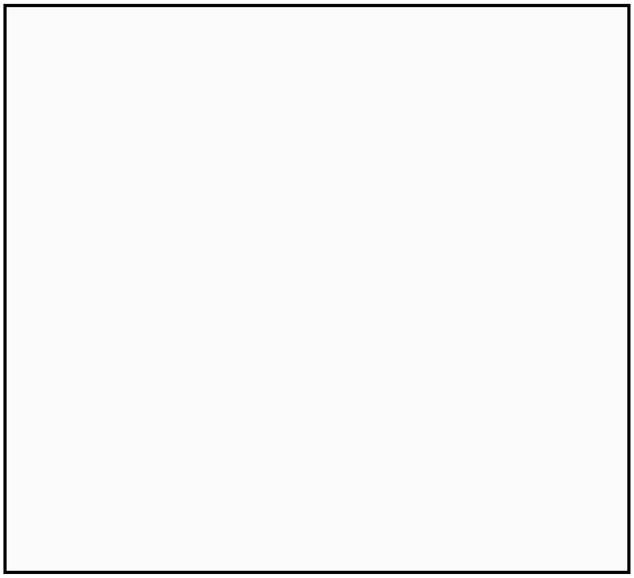


Figure 4: The Galactic Center, 24,000 light-years distant, is seen only as a blur of light in a standard telescope image (lower left inset box). But with the Keck II Adaptive Optics instrument turned on (lower right inset box), sharpening the image from 0.5 arc-second to 40 milliarcsecond resolution, many individual stars located within a light-week of the central black hole are revealed

2.1.2.4 Extended Objects – Solar System

The scientific goal of this program is to study objects in the outer solar system that retain information about conditions in the early solar system. (PIs: Brown, de Pater, Macintosh). From an AO standpoint, this aspect of our program focuses on studies of Solar System bodies which have small apparent sizes, and thus are ideally suited to observation using AO. In year one, we concentrated on Neptune, Titan, and Io – bright, compact objects that are good trials for new observing techniques;

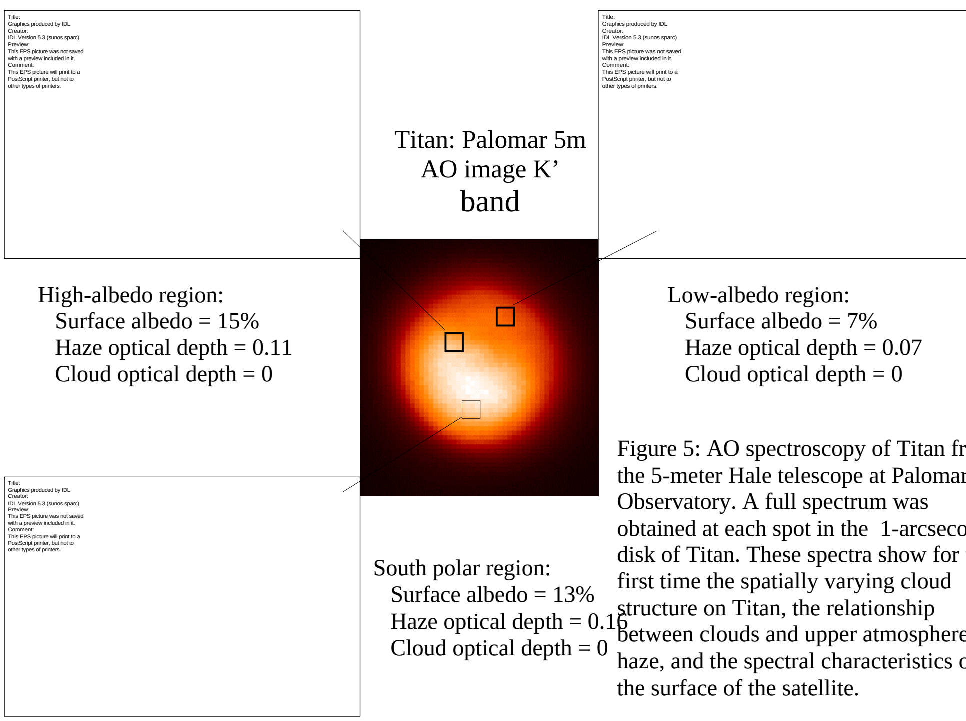


Figure 5: AO spectroscopy of Titan from the 5-meter Hale telescope at Palomar Observatory. A full spectrum was obtained at each spot in the 1-arcsecond disk of Titan. These spectra show for the first time the spatially varying cloud structure on Titan, the relationship between clouds and upper atmosphere haze, and the spectral characteristics of the surface of the satellite.

initially using imaging and then AO spectroscopy (see Figure 4). In Year 2, the Center groups will begin to apply deconvolution techniques optimized for sharp-edged planetary objects, and for AO spectroscopy.

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

Faculty/Senior Researchers: James Brase* (LLNL), Gary Chanan*(UCI), Sandra Faber* (UCSC), Scot Olivier (LLNL), Shri Kulkarni (CIT), David Koo (UCSC), Raja Guhathakurta (UCSC), Ed Kibblewhite* (UChicago), Andreas Quirrenbach* (UCSD), Ridgway Scott (U Chicago)
Research Scientists: Julian Christou (UCSC), Richard Dekaney* (JPL), Don Gavel (LLNL), Bruce Macintosh (LLNL), Carmen Carrano (LLNL), Eric Johansson (LLNL), Andrew Phillips (UCSC), Vesa Junkkarinen (UCSD), Anshu Dubey (U Chicago), Ernesto Gomez (U. Chicago)
Postdoctoral Researchers: Ben Oppenheimer (UCB), Jennifer Patience (LLNL), Matthias Shoeck (UCI), Christopher Willmer (UCSC), Eric Steinbringer (UCSC), Ben Weiner (UCSC)
Staff: Mitch Troy (JPL), Lin Zhou (U Chicago), Vijuna Scor (U. Chicago)
Students: Sasha Hinkley (UCSC), Catherine Ohara (UCI), James Marshall (UCLA), Lynne Raschke (UCSC), Patrik Jonsoon (UCSC), Neda Safizadeh (UCSD), Jennifer Roberts (UCSD), Hyo Joon You (U. Chicago)

Center efforts directed towards Goal 2 may be divided into two categories. The first is the development of tools to understand and use adaptive optics – focussing initially on the most difficult question in astronomical adaptive optics, the nature of the AO point spread function (PSF), and on the development of software tools for processing adaptive optics data. The second is knowledge transfer within the astronomical AO community - the process of disseminating knowledge of AO capabilities and techniques to a broader audience and of connecting the Center to leading non-Center researchers in these fields.

2.2.1 Point spread function determination

Determination of the point spread function (PSF), i.e., the response of the imaging system to a point source, is one of the central difficulties in astronomical adaptive optics. Several groups within the CfAO (LLNL, UCI, UCLA, UCSC, UCSD) are therefore working together to develop tools that allow for a better characterization of the PSF from images taken with AO cameras, from wavefront sensor data, and from a priori simulations of AO systems. These efforts feed into other Center goals; knowledge of the PSF is crucial to planning AO science and to interpreting the results (Goal 1), and understanding of AO system performance guides the enhancement of the current generation of systems and instruments and the development of the next (Goal 3 and 4).

One of the projects carried out during year 1 has been to construct an accurate simulation of the Keck AO PSF at large field angles, and to construct an error budget based on diagnostic data from the wavefront control system that accurately predicts the Strehl of the Keck AO PSF (PI: Brase). These two elements are the first steps towards being able to predict the PSF using diagnostic data, and then using the predicted PSF to deconvolve astronomical data. In order to construct an accurate simulation of the Keck AO PSF, a closed loop simulation capability for the Keck AO system has been developed with the ability to include many parameters and features of the real system: phase aberrations of the primary mirror segments, the pupil shape, and the science camera.

Figure 6 shows a comparison of the real and simulated Keck PSF. The real Keck PSF exhibits short streaks distributed radially at periodic distances from the central star and arranged in an azimuthal pattern around the star, that are a noise source in attempts to detect faint companions or circumstellar structure (2.1.2.1). These streaks have been observed to rotate when the pupil rotates, which would suggest that some property of the primary mirror is causing them. Investigation of high-resolution wavefront sensor data taken of the individual segments, provided by the Center project on segmented-telescope AO, revealed a particularly suspect feature in every reconstructed phase image, that of a central dimple ~15 cm in diameter. These dimples are due to the segment lateral support structure. Figure 7 shows an example of the segment phase with a central dimple.

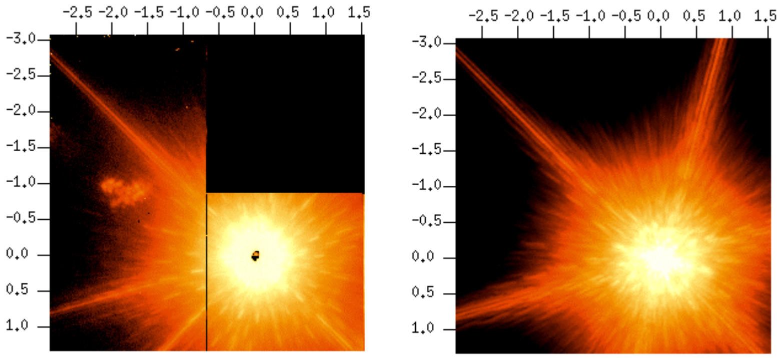


Figure 6: Real and simulated Keck images. The simulated image has been shifted and rotated to match the appearance of the real image. The display minimums and maximums for the two images are set to be the same. The x and y axis units are in arcseconds. The blob at –2, -1 in the real image is a camera ghost.

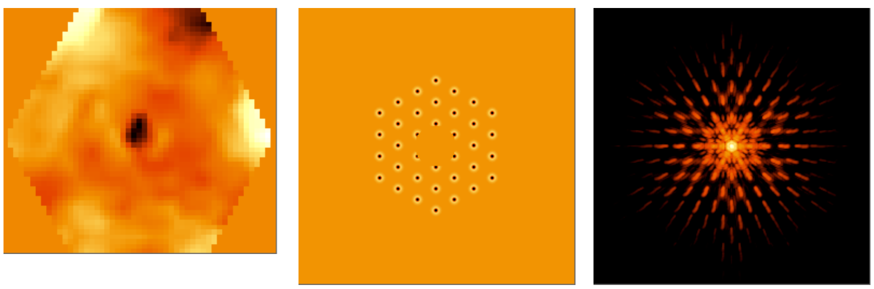


Figure 7. Phase image of segment 36 reconstructed from fine segment WFS data (peak to valley wavefront is ~540 nm) along with phase in the pupil plane from a dimple in the center of each Keck segment and corresponding PSF in H-band.

The magnitude of the wavefront error from the dimples has been measured to be from 300 to 600 nm peak-to-valley in a sample of 7 segments. To illustrate the effect that a dimple of this sort would have on a PSF image, Figure 7 also shows a simulated phase image with dimples only and a corresponding H-band PSF image, with no atmospheric or AO effects. Note the striking resemblance between the streaks in this simulated PSF and those found in the real Keck image. When a full AO simulation with atmosphere is included (Figure 6) the image is almost indistinguishable from the true Keck deep PSF. This result demonstrates convincingly that careful simulations can lead to a detailed understanding of the PSF and to subsequent improvements of the telescope and adaptive optics system. These simulations also determined that the dimples have little effect on the overall telescope phase map and Strehl ratio, since they occupy so little area; only in high-contrast imaging of targets near bright point sources does the light they scatter become significant. This is an excellent example of Center synergy. Data and skills from three different groups – astronomical scientists from UCLA with deep Keck AO images, Keck segment figure data from UCI wavefront measurements, and LLNL AO simulation software – came together to solve a crucial problem in understanding the science performance of the Keck AO system.

2.2.2 Adaptive Optics Systems on Telescopes with Segmented Mirrors (PI: Chanan)

Telescopes with segmented primary mirrors present challenges for adaptive optics systems, which cannot easily deal with the discontinuities that occur at the edges of the individual segments. The CfAO is developing improved algorithms for phasing segmented mirror telescopes in order that the associated phase errors not limit the performance of their AO systems. This work is important for AO at Keck and even more important for the proposed extremely large telescopes of the future.

The current Keck telescope segments are aligned using a sequential process that is excellent for non-AO imaging, but may optimize image stacking at the cost of greater phase discontinuities at segment boundaries. Since AO systems have difficulty dealing with discontinuous wavefronts, but are well-equipped to handle errors of low spatial frequency, it may be beneficial to exchange the high spatial frequency errors associated with the edge discontinuities for errors of lower spatial frequency content. This can be done by deliberately mistilting the segments to minimize these discontinuities (at the segment midpoints, inducing low-order aberrations instead that the AO system can easily correct). To date one test of this AOSTACK vs. the normal configurations has been carried out to observe the effect on the PSF. The results were not conclusive, but this is not particularly surprising or discouraging. It likely indicates that Keck AO is currently limited by other effects than those associated with segment phasing and alignment — in itself an interesting and important conclusion, showing that there is nothing fundamental about segmented telescopes that limits their performance with AO, also supported by results when true segment figures are incorportated into AO simulations (2.2.1). This connects with the Center's projects to study advanced AO for large telescopes (Goal 4.)

2.2.3 ***Software Distribution (PI: Quirrenbach)***

The productivity of the AO systems that are operational to date is (at least partially) limited by the lack of easy-to-use data reduction routines, and of guidance to the observer through the planning, calibration and deconvolution processes. The CfAO has therefore begun to organize and document existing AO data reduction software, to make it accessible to the user community on the CfAO web page, and to coordinate further AO software development.

The first software package that has been made available on the UCSD CfAO web page is A^{++}. This package can be used to determine the atmospheric wavefront from discrete slope measurements (i.e., Shack-Hartmann wavefront sensor data) and to explore innovative techniques for control of AO systems at visible wavelengths. It has been used to generate the control matrices for a number of the AO systems that are now operational at astronomical observatories. The A^{++} software was written at U Chicago and is now available for general use on a PC platform. The software allows the systems designer to specify the geometry of the wavefront sensor and deformable mirror using a graphical interface, and to generate appropriate reconstruction coefficients.

Also available on the UCSD CfAO web page is *StarFinder*, complete with documentation, test data sets, and an introductory tutorial. *StarFinder* is an IDL program for photometric analysis of stellar fields developed at ESO and U Bologna. It detects stars and determines their positions and relative fluxes. It has been designed specifically for adaptive optics data, keeping in mind the complex AO PSF. The complexity of the PSF might lead to false detections and can affect the photometry of faint objects. On the other hand the good sampling of a typical AO observation is an important advantage that is properly exploited. *StarFinder* should be a very useful tool for anybody wishing to analyze AO observations of stellar clusters, and a good starting point for further research on PSF characterization and the effects of anisoplanatism. A real-time demonstration of AO data analysis at the CfAO Summer School was also done with the *StarFinder* package.

2.2.4 Workshops

The following workshops have been organized by the CfAO:

- Wavefront Detectors (Santa Cruz, CA, Nov 99)
- Micro-Electro-Mechanical Systems (Santa Cruz, CA, Nov 99)
- Sodium Laser Development (Santa Cruz, CA, Dec 99)
- Adaptive Optics 101 (Berkeley, CA, Feb 00)
- AO Data Reduction Software (Greenbelt, MD, Feb 00)
- Laser Beacons (Lake Geneva, WI, Jun 00)
- CfAO / NOAO Summer School on Adaptive Optics (Santa Cruz, CA, Jul 00)

Most of these meetings were two-day workshops that brought together specialists in the respective fields from the Center and other US and international institutions. The main purposes of these workshops were: summarizing the current state of the relevant technical areas, discussing the contributions that the CfAO can make over the next few years, and coordinating the work performed at the different CfAO sites and by the partner institutions.

The character of "Adaptive Optics 101" held in Berkeley and of the Summer School was different: here the primary goal was the dissemination of basic knowledge about adaptive optics, the main target audiences being graduate students and postdocs. At the Summer School, which lasted 6 days and was attended by more than 90 participants, 24 lectures of 75 minutes each were delivered by 17 speakers. The program was designed to be a balanced mix of introductory topics, vision science, and astronomical aspects of adaptive optics. The presentations given at the Summer School will be published as a hardcover book by the Astronomical Society of the Pacific.

2.3: Goal 3 - Development of Advanced Instruments for Adaptive Optics

Faculty: James Graham* (UCB), James Larkin* (UCLA), Claire Max (LLNL), Don Miller* (IU), Andreas Quirrenbach (UCSD) & Austin Roorda* (UH)
Research Scientists: Bruce Macintosh (LLNL), Fernando Romero (UH), Scott Severson (UCSC)
Postdoctoral Researchers: Paul Kalas (UCB), Jiyuan Liu (IU), Ben Oppenheimer (UCB), Huawei Zhao (IU)
Graduate Students: Matthew Barczys (UCLA), William Donnelly (UH), Chiyu Liu (UH), James Lloyd (UCB), Joseph Rhee (UCLA), Abhiram Vilupuru (UH), Fan Zhou (IU)
Engineers: George Brims (UCLA), Xiaofeng Qi (IU), Michael Spencer (UCLA), Jason Weiss (UCLA)
Collaborators: Larry Thibos (IU), Arthur Bradley (IU)
* indicates PI of a Center Project in this Goal.

Adaptive optics provides both new capabilities and also new challenges for scientific instrumentation. In astronomy, the angular resolution can be as much as 20 times higher than without AO, and so the physical sizes of instruments are often an order of magnitude smaller, and the optical and mechanical quality of components must be higher. Also the field of view is limited by isoplanatic effects and there is a strong variation in point spread function with wavelength. In ophthalmology, the ability to resolve individual photoreceptors allows for entirely new techniques in studying the eye. A prime example of this is the potential to optically section photoreceptors in three dimensions. The center has made the development of new instrument capabilities that are matched to advanced AO systems a primary objective.

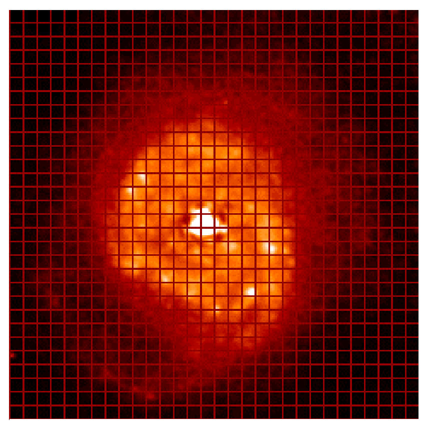


Figure 8 - This AO image of the AGN and surrounding region of Mrk 231 (from CFHT) illustrates the concept of an integral field spectrograph. In the Keck instrument, a lenslet will take the light from each grid location and produce a high resolution spectrum.

2.3.1 Astronomical Instruments

2.3.1.1: AO integral field spectrograph (PI: Larkin)

The UCLA infrared laboratory is currently designing an integral field spectrograph for the Keck AO system. The goal of the current instrument design is to produce spectral data cubes with near diffraction limited spatial resolution. The concept uses a cryogenic lenslet array to obtain infrared spectra at over 1000 locations simultaneously (Figure 8.) Most traditional techniques for non-AO instruments are difficult to scale to AO resolutions and several methods were investigated. The final instrument will use a lenslet array, virtually identical to the type in wave front sensors, to sample the rectangular field of view. During the first year, a formal concept was developed and a testbed spectrograph was created using an optical CCD and off the shelf optics. The final design was presented to the Keck Observatory as a third generation instrument. The spectrograph was selected as the only new instrument design to be approved at Keck to go forward to preliminary design review. In the 2nd year, future concepts like the use of fiber optic bundles will be investigated, and the Keck instrument will be developed through to a critical design review.

2.3.1.2 AO Coronagraphs: (PI: Graham, Dekaney)

One of the principle advantages of diffraction-limited imaging is that it increases image contrast, so that a faint object can be detected close to a source that under conditions of normal imaging would swamp it. Coronagraphy coupled with AO is a way to achieve even better dynamic range. The IRCAL team has been designing coronagraphic masks for use at Lick. In the upcoming year they will fabricate and install masks within IRCAL and they have extended their modeling to the potential use of the Air Force AEOS facility. The capability to simulate AO performance (Goal 2) allows coronagraphs to be carefully optimized for best contrast.

2.3.1.3 Compact AO spectrographs (PI: Graham)

There are significant scientific rewards if AO can be combined with spectroscopy. An efficient way to implement spectroscopy is with a grism (hybrid prism/grating). Most grism materials, however, have low refractive indices (n~1.5) which makes it difficult to create high dispersion instruments. Moreover, classical fabrication techniques limit the groove density to >30 grooves/mm limiting the order of interference, making a cross-dispersed instrument with wide spectral coverage impractical. Within the IRCAL camera developed at UC Berkeley and operated with the Lick AO system new silicon grisms were tested during the first year. Created at LLNL by a team led by Jian Ge (now at Penn State), these silicon grisms have a high index of refraction (3.4 at 2.2 μm) and are micro-fabricated with a very coarse ruling. The first grisms have some problems with ghosting and surface imperfections but allowed the camera to become a spectrograph with a resolution of 5500 and complete K-band coverage (Figure 9), compared to ~500 for a conventional calcium fluoride grism in the same camera, or ~150 for a CaF grism in a non-AO camera. Solutions to the initial problems are in hand and during year 2, new grisms will be tested as well as anti-reflection coatings.

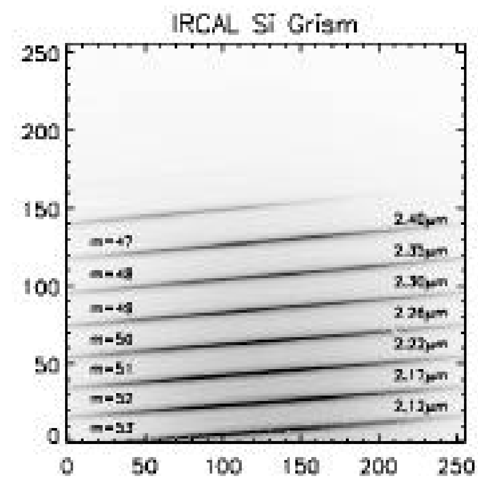


Figure 9 - Cross-dispersed Si Echelle orders from a 46 degree wedge angle, 15.2 grooves/mm grism. With a conventional CaF2 grism used for cross-dispersion, the arrangement provides complete coverage of the K-band at R~5500.

2.3.1.3: AO user instruments:

As one of the main AO instruments available to center scientists, IRCAL's operation and optimization are crucial for many scientific efforts. During the first year significant work has gone into improving its interface both to the AO system and to users. Of particular importance is the reduction of non-common path aberrations that the AO system cannot sense. During the next year, an additional communications between IRCAL and the AO system will automate the phase diversity algorithm which is used to compute the static aberrations that the AO system misses. Significant scientific observations are planned with this system by several center members during the upcoming year.

2.3.2 Vision Instruments

Vision science AO now has the ability to study the human retina in its focal plane, i.e. in two dimensions. However, the retina is a complex three-dimensional structure. The next step in vision AO is to develop instruments capable of "optically sectioning" the retina, individually imaging each layer of a living eye. Two approaches are being developed: a coherence-gated retinal camera and a scanning laser ophthalmoscope.

2.3.2.1: Coherence-gated retinal camera (PI: Miller)

Coherence gating provides exceptional axial resolution and optical slicing capability. It is realized with a Michelson interferometer and a low temporal coherence light source. The low coherence limits interference from only a thin layer in the tissue that resides at the same optical distance as the reference mirror. Intensity and phase profiles of the tissue layer are reconstructed from several recorded interference patterns. High *transverse* resolution will be realized with adaptive optics. Together adaptive optics and coherence gating can provide the three-dimensional resolution necessary for imaging low-contrast structures buried in the light-scattering retina.

In the first half of year one, a design was finalized for the coherence-gated component of the retinal camera that will be constructed at Indiana University. As this methodology has not to our knowledge been applied before to biological tissue, it was necessary to construct a prototype from which the design could be fully tested before introducing adaptive optics. To this end, we purchased the necessary optical and electronic equipment (including a Photometrics Quantix 57 CCD camera) and have begun to construct a prototype system on a 5'x8' optical breadboard. Results will be obtained with an artificial eye consisting of an achromatic doublet and extracted bovine retinal tissue. Preliminary imaging results with this camera are expected in the summer of 2000. The design for the final coherence-gated camera for imaging living human retina is shown in Figure 10.

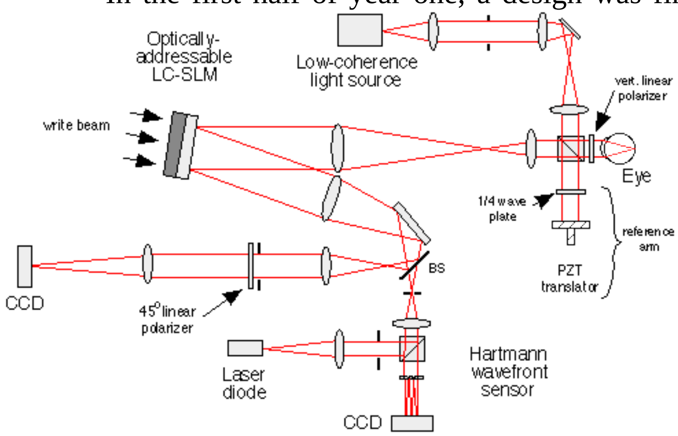


Figure 10. High-resolution coherence-gated retinal camera. The camera's principle components include a low-coherence light source ($\Delta\lambda < 25$ nm) for illuminating the retina, a Hartmann sensor for measuring the eye's ocular aberrations, an optically-addressable LC-SLM for correcting these aberrations, and a high frame rate scientific-grade CCD camera for recording interferograms and intensity images of the illuminated retina.

In Year 2, using the experience gained with the prototype system built in year one, Indiana researchers will re-engineer the camera for collecting retinal images in living eyes. The re-engineering will involve: (1) identifying a low-coherence light source for illuminating the retina, (2) integrating a fast and accurate PZT translator for axial movement of a reference mirror, and (3) control software.

An AO system will be integrated into the camera, The development of the AO system will require: (1) determination of the most appropriate type and configuration of commercial wavefront sensor and corrector, and (2) development of software to process the sensor data and to control the corrector. Specifications for the AO system will rely on the optimization results obtained for the wavefront sensor (University of Rochester) and corrector (Indiana University).

2.3.2.2: Scanning Laser Ophthalmoscope (PI: Roorda)

At Houston a primary goal is to build a scanning laser ophthalmoscope (SLO) as an alternative method of probing the three dimensional structure of photoreceptors. During the first year we have created an optical testbed for development of the wavefront sensing and compensation system that will be implemented into the SLO. The design of the SLO was also completed and a parts list has been compiled. Within the first year, the deformable mirror will be fully functional. Much of the SLO will also be assembled, although light detection electronics will still be under development. During the 2nd year, the SLO will be integrated with the AO system and they will begin a trial to collect images of the retinas of a group of volunteer subjects. By the end of the 2nd year, we hope to create a complete system with wavefront sensing, compensation and operation of the SLO all within a single integrated system with one computer. This is a major step towards an instrument that might be practical for the broader use of ophthalmologists.

Houston plans to obtain the first AO-SLO images of the living human eye in the second grant year and complete imaging studies on the optical slicing capabilities of the system. They also plan to integrate wavefront sensing/compensation and the scanning laser ophthalmoscope into a single system run by one computer.

2.4: Goal 4: Advanced Adaptive Optics

Principal Scientists/Faculty: T. Bifano (BU); E. Kibblewhite*, (U. Chicago); I. McLean* (UCLA); R. Muller* (UC Berkeley); J. Nelson* (UCSC); S. Olivier* (LLNL); S. Payne* (LLNL); B. Sadoulet, (UC Berkeley); D. Tytler* (UCSD)
Research Scientists: B. Bauman(LLNL); R. Beach (LLNL); .J. Brase (LLNL); G. Brims (UCLA); C. Carrano (LLNL); W. Cowan (AFRL); R. Dekany (JPL); F. Doula (LLNL); E. Ebbers (LLNL); G. Erbert (LLNL); M. Kartz (LLNL); P. Krulevitch (LLNL); T. Mast (UCSC); J. T. Murray (Lite Cycles); H. Nguyen (LLNL); R. Page (LLNL); S. Payne (LLNL); D. Pennington (LLNL); C. Thompson (LLNL); J. Yu (LLNL)
Postdoctoral Researchers: D. Kirkman, (UCSD); D. Lande (LLNL); M. Le Louarn (UCSC); C. Rembe, (UC Berkeley)
Staff: R. Sawvel (LLNL); D. Silva (LLNL); G. Skulason (UCLA); L. Zhou (U. Chicago)
Students: E. Carr, (UC Davis); H. Choo (UC Berkeley); M. Helmbrecht, (UC Berkeley); A. Puckett, (U. Chicago); M. Wilcox (UCLA) V. Cano (U. Chicago)

2.4.1 Overview

The goal of the Advanced Adaptive Optics program is to develop a new generation of component technologies for adaptive optics in astronomy and vision science. The program elements include new laser technologies for astronomical laser guide stars, new wavefront control and correction technologies for both astronomy and vision science, and advanced concepts for tomography on giant astronomical telescopes. The most important deliverables will be compact and efficient lasers, MEMS (Micro Electro Mechanical Systems) deformable mirrors of high optical quality, and the design and simulation of tomographic AO systems.

2.4.2 Advanced laser technology

If only natural stars are used to measure the turbulence in the earth's atmosphere, at most only a few percent of the sky is accessible to adaptive optics correction. Laser guide stars are therefore crucial to the broad use of adaptive optics. In particular, lasers tuned to the 589 nm resonance line of atomic sodium are able to create an artificial beacon at altitudes of 95-105 km, thus coming as close as possible to reproducing the light path of starlight.

During the past year the CfAO pursued two general paths toward the development of advanced sodium laser guide stars based on diode-pumped solid-state laser technology. First, we are developing pulsed sum-frequency lasers using existing prototype laser heads as well as a new head. This technology should be deployed at a telescope within one to two years. For the longer term, we are studying new approaches to high-power CW sum-frequency lasers.

2.4.2.1 Pulsed sum-frequency laser: (PI: Kibblewhite).

Pulsed sum-frequency lasers have potential advantages in the efficient use of laser power. This year we improved our existing prototype laser by rebuilding its cooling system and optimizing the thermal lensing in the laser slab. We designed and are implementing a new sum-frequency conversion module based on three in-line LBO crystals. To develop a robust second-generation laser design, we have joined in a consortium with the Gemini Observatory, the NSF, and the Lite Cycles Corporation to build three new gain modules. Once these second-generation gain modules are ready, our advanced sum-frequency conversion module will be used for the new laser. The advanced laser is expected to deliver up to 20 watts of 589 nm light. In Year 2, the second-generation laser system will be assembled, tested, and optimized in the laboratory. If these initial tests are successful, planning will begin for laser installation at an observatory site to be selected, and installation will commence.

2.4.2.2 CW sum-frequency laser: (PI: Payne)

Continuous-wave (CW) lasers have potential advantages in robustness, and in their ability to be transmitted through optical fibers. This year we performed a design study to compare new approaches for robust, high-power solid-state lasers capable of operating for long time periods in a remote observatory environment. We identified three promising design approaches based on sum-frequency mixing: 1) A master oscillator-power amplifier design in which the two wavelengths are amplified before being mixed in new nonlinear materials; 2) A dual-frequency resonator with intra-cavity frequency mixing in the traditional LBO crystal; and 3) Approaches based on fiber laser oscillators and amplifiers, with the sum-frequency mixing as in 1) above.

Improvements in the area of high power, high-brightness semiconductor pump lasers and the development of cladding-pumping have allowed fiber-laser technology to expand to high power applications. The greatest commercial infrastructure is in CW fiber lasers. In the coming year we will test two technologies key to the CW fiber-laser approach: a) Utilization of PPLN or PPLT (periodically poled lithium niobate and tantalate) sum-frequency crystals at high laser powers (e.g. 10 watts) using anamorphic beam shaping to reduce the light intensity inside the material; and b) testing of a new sum-frequency concept which utilizes an Er doped fiber laser at 1583 nm and a 938 nm silica fiber laser. We will first test the 938 nm silica fiber laser, a relatively unexplored concept. If the PPLN/PPLT tests are successful, we will establish an industrial partnership to commercialize these crystals for high-power applications.

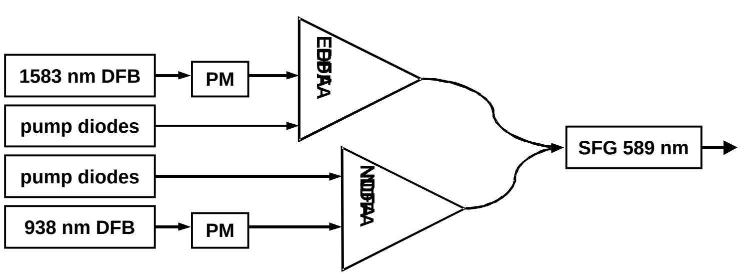


Figure 11: Block diagram of the fiber laser system. Laser is based on sum-frequency generation (SFG) of two fiber lasers in a periodically poled material. Distributed feedback (DFB) fiber lasers provide the two input laser signals. A Nd:doped fiber amplifier (NDFA) amplifies the 938 nm wavelength, while an Er:doped fiber amplifier (EDFA) amplifies 1583 nm light. Phase modulation (PM) suppresses Brillouin scattering in the fibers.

2.4.3 Advanced Technologies for Wavefront Control and Correction

Compact, reliable, and low-cost wavefront control and correction technologies will be needed for visible-light adaptive optics at large astronomical telescopes, as well as for high-order correction of aberrations in the human eye. The CfAO is spearheading adaptive optics applications of silicon Micro Electro Mechanical Systems deformable mirrors (MEMS DMs) and liquid crystal spatial light modulators for wavefront correction, and of next-generation infrared detectors for wavefront measurement. In addition to developing and optimizing these components for adaptive optics applications, the CfAO is developing a laboratory test-bed to be used for systems integration and demonstration of these technologies in a closed-loop adaptive optics system.

2.4.3.1 MEMS Deformable Mirrors: (PI: Olivier, Sadoulet, Muller)

The first activity for this project was a CfAO MEMS development kickoff workshop at UCSC, at which a MEMS development plan was drafted. The aims of this plan include larger numbers of actuators and higher optical quality, and the implementation involves a consortium of eight institutions (see section 4.2 for more discussion of the relationships between the institutions.)

The plan includes three important risk reduction features: 1) Parallel development paths based on device designs from Boston University (BU) and the Air Force Research Laboratory (AFRL), which were already into development before the advent of the CFAO. 2) Utilization of the most established publicly available surface micro-machining fabrication processes for optical quality devices at Cronos Integrated Microsystems (CIM) and Sandia National Laboratory (SNL). 3) Packaging and drive electronics provided by Lucent Technologies based on their extensive investment in these areas, and by Boston Micromachines Corporation (BMC), a company working with Boston University. MEMS devices with 144 and 252 active elements are currently in the fabrication and testing stages.

The CfAO MEMS development plan is heavily leveraged from pre-existing programs at participating CfAO partner and collaborator institutions. The primary role of the CfAO has been to coordinate and focus these activities on specific technical goals relevant to the CfAO. In addition, a new effort at the Berkeley Sensor and Actuator Center (BSAC) was begun within the CfAO, which takes advantage of extensive BSAC expertise in design, fabrication, and testing of optical MEMS. This activity has developed designs with higher-stroke actuators (> 4 μm) using bimorph flexures, and has investigated two new techniques for transferring mirror segments to the actuators. The BSAC effort represents a third parallel development path emphasizing new techniques that could enable high-stroke devices with many actuators.

In Year 2, new MEMS devices will be fabricated and tested incorporating more degrees of freedom, higher optical quality, and improved high-stroke actuator designs. Processes will be developed for deposition of high-reflectivity coatings on existing MEMS devices. Methods will be investigated for dealing with the large number of interconnects needed for next-generation MEMS DM arrays, and for mirror/actuator assembly in large mirror arrays.

2.4.3.2 Laboratory test-bed and advanced AO technology demonstration: (PI: Olivier)

A laboratory test-bed was assembled, with an initial wavefront corrector based upon a compact liquid crystal spatial light modulator from Hamamatsu. This device is optically addressed, and is utilized with a 2000 subaperture Shack-Hartmann wavefront sensor. An efficient Fourier Transform-based wavefront control algorithm was implemented and successfully demonstrated. In Year 2, as new MEMS deformable mirror devices become available, one or more of these will be integrated into the laboratory test-bed, and demonstrated in closed-loop adaptive optics control. A second-generation wavefront sensor and an advanced real-time computer will be designed.

2.4.3.3 Next-generation infrared detectors for wavefront sensing: (PI: McLean)

A new family of high-speed, low-noise near-infrared detectors is being developed by Rockwell. On behalf of the CfAO, the UCLA group is working with Rockwell to resolve issues of importance to astronomical adaptive optics and to test the new devices. A test station was built at UCLA for this purpose, and multiple discussions were held with Rockwell to clarify the needs of the astronomical adaptive optics community. In year 2, the test dewar will be completed at UCLA, higher-speed electronics will be implemented for the test station, and initial Rockwell arrays will be tested for suitability as infrared wavefront sensors for astronomical adaptive optics.

2.4.4 Advanced Concepts for AO Tomography on Giant Telescopes (PI: Nelson, Tytler)

Atmospheric tomography is the process of making a three-dimensional map of the atmospheric turbulence using parallax over the baseline of the telescope. Our goal is to develop tomographic techniques of measuring atmospheric turbulence and its effect on starlight. If successful, these can be used together with multi-conjugate adaptive optics to dramatically increase the field of view of adaptive optics corrections. This will be of particular interest for the next generation of 30 to 50 m telescopes, since if operated with laser guide stars they will require the use of multiple laser beacons to reduce the so-called "cone effect" (a result of the fact that a single laser beacon generates photons that pass through a cone-shaped region of the atmosphere, rather than the cylindrical region sampled by natural starlight). These multiple beacons can be used as well to create a tomographic image of atmospheric turbulence.

In this first year we came up to speed on current research concerning atmospheric tomography, and consulted extensively with our partners B. Ellerbroek and F. Rigaut at the Gemini Observatory. We coordinated the work planned at UCSC and UCSD with ongoing research on multiconjugate adaptive optics at Gemini and other observatories, and successfully recruited two new post-doctoral fellows who are experts on tomography.

In year 2, we will investigate tomographic methods for removing the cone effect using multiple laser guide stars. Key issues are the required number, locations, and brightness of laser spots, as well as techniques for determining tip-tilt for the laser beacons. We will investigate optimum laser launch configurations and pulse formats. Our tools will be both analytic analysis and computer simulation, in collaboration with the LLNL AO simulation software (Goal 2.) We will benchmark our computer simulation codes at UCSC and UCSD with those of our partners at the Gemini Observatory, to increase our confidence in the results. We will design experiments to test crucial aspects of tomography using existing telescopes with CfAO AO systems.

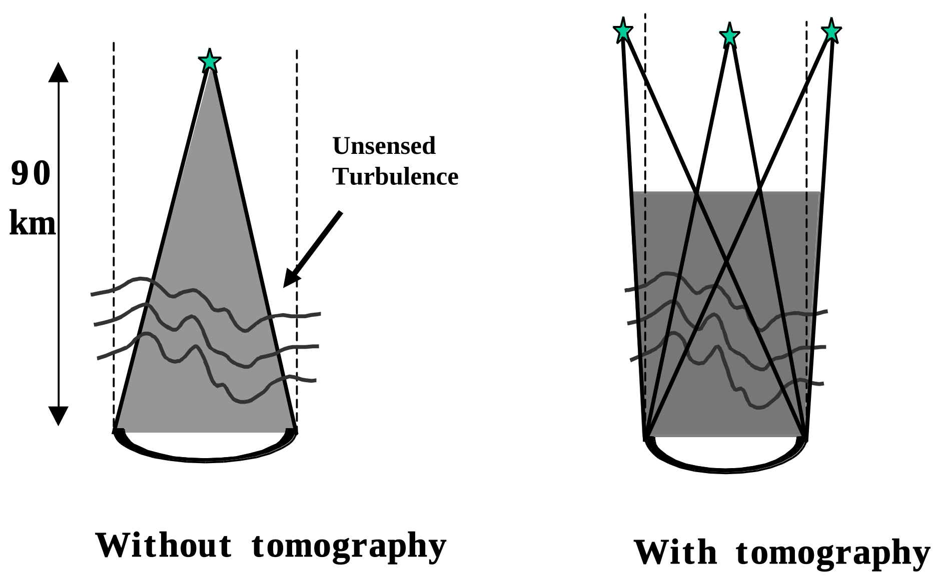


Figure 12. Schematic showing principle of atmospheric tomography using multiple guide stars. Turbulence at moderate altitudes (10-20 km) is only partially sensed with a single guide star (left). Using multiple beacons (right), the turbulence in the shaded area is completely sensed and its altitude can be recovered from tomographic comparison of the measurements on different beacons.

3: Education and Outreach

The goal of the CfAO's education and outreach program is to promote interest in science, through enriching both formal and informal science education at all levels. Specifically we are targeting underrepresented groups and minorities. Accordingly, the Center for Adaptive Optics has established a suite of programs spanning the educational continuum. This has been accomplished by forming strategic partnerships and building upon successful programs at our host institutions. Additional partners include museums, planetaria, other STC's, national laboratories, and public school systems. Based on our collaborators existing infrastructure, the Center has provided substantial financial (~15% total budget) and institutional resources to leverage these programs to higher levels of efficacy. Most importantly the CfAO provides intellectual resources (5% of each center member's time.) toward education and outreach activities, which naturally integrates center science and center scientists' excitement into our programs. A description of our activities follows.

3.1 K-12 Student Centered: The CfAO's precollege student-centered programs are aimed at preparing participants for college and stimulating them to take an interest in science math engineering and technology (SMET). A hands-on approach is emphasized and where possible astronomy and vision science examples are used to capture the attention and imagination of the participants. The demographic distribution of our programs reflects the geographical diversity of the Center being targeted at inner city African Americans in Chicago, Latinos in the California coastal regions, and native Hawaiians. While some programs focus specifically on astronomy and others more generally on math and science skills, the common thread that links them is the involvement of our Center scientists.

3.1.1 The Kids Around the University The Kids Around the University (KATU) program at UCSC provides many local elementary students and parents, their first exposure to a college campus and the potential of a university education. Carefully constructed afternoon visits to campus laboratories are reinforced by a classroom curriculum. Pre and Post visit evaluations demonstrate an increased awareness by participants, of educational options and the steps necessary to prepare for college admission. This is an excellent example of how CfAO has leveraged an existing program. The Educational Partnership Center (EPC) handles all programmatic details: logistics, curriculum, recruitment, etc. and the CfAO provides role models and instructors – real life Center researchers.

3.1.2 CfAO Yerkes Space Explorers At Yerkes Observatory in southeast Wisconsin, Professor Kyle Cudworth is utilizing the observatory laboratories, staff, and telescopes to nurture middle school student interest in science. The Yerkes Space Explorers program provides opportunities to observe celestial objects, interact with professional astronomers, and most of all question, explore, and discover the field of astronomy in a non-competitive environment. The program places a particular emphasis on the female participants, whose interest in science often wanes at this age. This year two groups numbering 15 & 20 (30% & 15% female) attended. The Yerkes Space Explorer laboratories will be presented at the National Science Teachers (NSTA) meeting in Milwaukee this fall and will include those projects that utilize astronomical data collected at Yerkes (e.g., distance to stars, proper motion measurements) along with practical teaching tips for the classroom setting. This program was inspired by the highly successful, more intensive Chicago Space Explorers program described in 3.1.6 below.

3.1.3 Early Academic Outreach Program (EAOP) This effort focuses on the minority population (largely Hispanic) in the California coastal region. It targets lower income middle and high school students, helping them towards gaining college eligibility via Saturday teaching sessions. It also seeks to develop a cadre of student role models from this target group via Summer Youth Leadership Conferences (SYLC). To date the Saturday Colleges have focused exclusively on skills in English and

Math. The CfAO in partnership with EAOP is developing a new “Saturday Math and Science Academy” which for the first time will add a science emphasis to the existing model. The SYLC is a four-day, summer, residential, experience at Santa Cruz intended to cultivate academic leadership at the high school level. Participants attend workshops and take college level courses aimed at developing critical thinking and articulation skills. The workshops provide career planning and preparation for college and financial aid applications. The academic programs provide up to 5 high school course credits. Six leadership groups of eighty students will cycle through the SYLC this summer partaking in an assortment of college preparatory activities including an astronomy short course being organized by CfAO scientist R. Guhathakurta with seven other CfAO members. In addition to these academic preparation programs, the Center is playing a significant role in three long-term immersion programs that emphasize math and science.

3.1.4 COSMOS (144 attendees, 40% underrepresented minorities, 58% female, 41% full scholarship) At Santa Cruz, the California State Summer School in Math and Science (COSMOS) program is being offered for the first time. This is a four-week residential experience intended to motivate academically gifted high school students by providing opportunities for in-depth investigations of advanced topics presented by CfAO scientists. COSMOS students are from California and selection is based on their interest, talent, and achievement level in math or science. The program is run by the EPC, and students enroll in a series of two two-week short math and science based courses. CfAO provides the academic “pinning” - instruction via its scientists, financial support of scholarships. The academic director is G. Andreasen, Ph.D., who has a joint EPC/CfAO position. Eighty of the 144 COSMOS students specifically requested an astronomy course, but only 24 could be accommodated. However, all residential summer participants will be exposed to the forefronts of astronomy as six CfAO researchers are presenting four of the plenary Discovery Lectures to the COSMOS students and those from the Upward Bound and LA Basin Initiative programs. In addition, several CfAO researchers (S. Faber, R. Guhathakurta, D. Koo, & I. de Pater) are meeting with small groups of 4-8 COSMOS students for tours of the Lick Observatory shops and informal conversations. UC Irvine, which is a CfAO node, is the other site for this premier year of the COSMOS program and we plan to repeat as many of the Center Lectures at Irvine as possible this year or next. Finally, we plan to recruit a CfAO scientist to lead an astronomy course next year.

3.1.5 Upward bound (36 summer attendees, 84% underrepresented minorities, 51% female) Upward bound is a federally funded program for high school students designed to: 1) develop academic skills 2) help students stay in school and graduate and, 3) increase eligibility for college admission. Focusing on math and science, the UCSC/EPC program has two interrelated components: a four-week summer residential experience and an academic year follow-up. A highlight of the summer experience is the Discovery Lectures being presented by CfAO scientists and the more informal Dessert Talks where students and faculty have a chance to meet each other. Center plans include strengthening the role of CfAO researchers in the program, for example as mentors for independent research projects, and connecting these students with their peers in other urban environments where the Center has programs (e.g., Oakland and Chicago).

3.1.6 Chicago Space Explorers (30 participants, 100% African American, 70% female) The Chicago Space Explorers program is a multi-year commitment that aims to increase interest and abilities in math and science of inner city African American high school students. It is being offered in collaboration with the Center for Astrophysical Research in Antarctica (CARA). The program includes hands-on laboratory activities twice a week at The University of Chicago and Adler Planetarium during the academic year, a 1-week residential summer science institute at Yerkes Observatory, a 3-day winter institute at Yerkes, additional field trips, enrichment activities, and college tours for successful high school juniors (e.g., spring ’99 west coast college tour to UCB, UCLA, UCSC & Caltech nodes). The Space Explorers program is based on the core principals of: (1) using hands-on (laboratory) activities, (2) providing multi-year involvement, (3) conducting residential experiences, and (4) assuring parental involvement (Matyas et. al *Programs for Women and Minorities* pp67-96 AAAS 1991). The Space Explorer Program is unique due to its deep roots in the southside & University of Chicago communities, its long (10year) history, successful track record and the population it reaches. A recent survey found that 90% of past participants are attending college, 54% are SMET majors, and 94% of current Explorers expect to attend college. In contrast only 6 out of 10 students can be expected to graduate from Hyde Park Academy the main school from which where the students are drawn. Instructional staff include Center members R. Kron, K. Cudworth, and R. Landsberg; two graduate students and two Chicago public school teachers. CfAO’s collaboration with CARA has allowed center researchers to be meaningfully involved in the lives of thirty inner-city students interested in science and astronomy and has provided researchers with new perspectives which improve their communication and teaching. In the longer term CfAO researchers will become the Space Explorer teachers and mentors and in so doing continue a program that has consistently been heralded as a success particularly due to its long-term commitment to students.

3.2 K-12 teacher centered: A number of CfAO programs work directly with K-12 educators. They offer educators the chance to re-discover and get excited about science. These positive experiences are then hopefully amplified by translating them back to the classroom.

3.2.1 Chabot (30 teachers) In the San Francisco Bay area the CfAO has partnered with the Chabot Space & Science Center (CSSC), to work with the local K-12 community. Chabot, which is opening its new, $50 million, state-of-the-art facility this summer, has a long established record of outreach to the Oakland community. The Oakland Unified School District is one of the most diverse in the country: 48% African-American, 16% Asian/Pacific Islander, 17% Hispanic, & 48% low-income. We have co-developed a middle school teacher workshop, *Optics in Science, Optics in Nature*, that will be presented at Chabot on August 10 & 11 with follow-up during the academic year. Center scientists oversaw the workshop’s scientific content and will provide content and enrichment lectures during the workshop. Thirty teachers have been recruited for this year and the plan is to double the number of participants next year. A major goal of the development process and the workshop is to establish an ongoing relationship between Chabot and CfAO scientists, especially from Berkeley and LLNL which will enable other collaborative projects. The CfAO/CSSC partnership provides a rich opportunity to make optimal use of the Center's unique scientific resources (people and content) in the development and dissemination of learning materials. Center scientists B. Sadoulet, M. Issac, & G. Brasi are actively participating in this year’s workshop. In the future, Chabot’s facilities will enable distance learning with other center nodes, in particular we hope to partner teachers and students from Oakland with cohorts from Chicago.

3.2.2 Midwest Teacher Programs: (10 teachers, 50% female) In the Chicago area a powerful coalition of CfAO partners/members including The University of Chicago, Adler Planetarium, Carthage College of Kenosha, Wisconsin, and the Hands-on-Universe program are working together to offer teacher enrichment programs and to develop multi-media optics units that will be disseminated via Hands-on-Universe (HOU). HOU is a mechanism that utilizes image processing software to allow students and educators to analyze real astronomical data and to observe systems remotely. Over 1,000 schools and 30,000 students use HOU worldwide. The CfAO Optics module will supplement existing HOU modules and help students to understand the process of image formation, the limitations imposed on imaging by the physics of light, and ultimately, image degradation by the atmosphere and the use of AO. On June 12-16 CfAO hosted an initial development workshop for ten Wisconsin and Illinois public school teachers of grades 7-12 held at Carthage College and Yerkes Observatory. The workshop outcomes are currently being integrated into a draft HOU Optics module, which workshop participants will review. The revised draft will then be beta-tested during a follow-up workshop, August 10-13, where the teachers can work through the exercises in real-time. Workshop materials have been compiled and are posted on the Carthage College website at www.carthage.edu/departments/physics/CfAO, and will ultimately be disseminated via the HOU network (Website, CD ROM's, teacher workshops).

3.2.3 Pre-Service Teacher Enhancement (30 students, 93% female) Carthage College enrolls a large number of students preparing for careers as primary and secondary school teachers. These students are required to take a *Science Teaching Methods* course, which is traditionally taught by members of the Education Department, with little input from scientists. As part of the Center's outreach activities, the CfAO and the Carthage physics department provided input and support to the course with a three-phase set of activities. The education students were given experience with (a) the setup, operation, and use of telescopes; (b) astronomical images and data available through the Web, including a discussion of the basic physics of several classes of objects; and (c) a planetarium experience, which covered not only the basics of the night sky, but also the impact of light pollution. The students in the course also generated written assignments, which translated the science and laboratory ideas proposed by researchers into actual classroom curriculum aligned with the National Science Standards. These materials then reached hundreds of students in the Kenosha and Racine public schools through student teaching exercises.

3.4 Technical Training: *ALU LIKE*

The CfAO as part of the larger astronomy community has a large investment and a social responsibility in the Hawaiian Islands. While the approximately two dozen observatories located on Mauna Kea and Haleakala are significant employers of technicians in optics and electronics, native Hawaiians are grossly under-represented. To address this situation, the Center has partnered with the highly respected Hawaiian job-training group *ALU LIKE* to develop a program aimed at training Hawaiian optical technicians. The overall goal is to develop a cadre of Native Hawaiian technicians qualified to work at the observatories in Hawaii and a job placement network. The Center has initiated a plan to train Native Hawaiians through paid internships where they will be mentored by CfAO researchers. Currently interns are being placed at the LLNL Adaptive Optics group where Center funds are matched by LLNL. This past year, two Native Hawaiian trainees, Kristian Keahi and Shordon Lopes, spent six months at LLNL. They received training in general technician skills, in AutoCad, and optical design. They assisted with optical and electronics tasks related to the Lick Observatory adaptive optics system, and became an integral part of the adaptive optics observing runs at Mt. Hamilton. They visited three Hawaiian observatories (Keck, Gemini, and Canada-France-Hawaii), where they held discussions with electronics and mechanical engineering staff. Shordon Lopes is now working at the W. M. Keck Observatory on Mauna Kea, and Kristian Keahi is on Kauai at Textron Systems, which will co-fund her college tuition. Both trainees have decided, as a result of their experience with CfAO, that they must complete their college education. Recently two more students have begun their internships at LLNL: Edward Akana, II, a student from Honolulu Community College, and Kehau Apana, a high school graduate from Nanakuli High School. This program has great potential for expanding as currently only one CfAO node is being used for internships and many more native Hawaiian candidates can be recruited. However, such an expansion will require additional resources beyond the scope of the center, potentially from the ATE program.

3.5 University Level:

Center faculty bring the excitement and discovery of their research into undergraduate and graduate courses. For example, Don Miller involved 90 optometry students in a “clinical trial” of wavefront aberrations. This provided the students with first-hand research experience as both patient and physician with one of the few existing Hartmann-Shack wavefront sensors. In addition the CfAO affiliation expands research options and connects undergraduate students, graduate students and post-doctoral researchers to a large network of collaborators including senior scientists from other institutions and industry. The Center is also supporting specific efforts to improve undergraduate physics curriculum, to help young researchers better manage their careers, and to bring AO into the undergraduate classroom.

3.5.1 Undergraduate Physics Many students in introductory physics courses at college intend to seek careers in medicine and the biological sciences, for example fully two-thirds of the students at the University of Rochester are in these categories. Center scientists at U. Rochester and U.C. San Diego are making physics coursework more relevant to such students by developing laboratories that incorporate vision science and optics relevant to biological sciences (e.g. microscopy). Vision science and biological science capture the interest of these students. The human eye and brain represent a most remarkable imaging system and can be used to illustrate a number of fundamental physical principles. A. Maheshwari, a graduate student in biomedical engineering, and D. Williams developed a lab on image formation based on the ophthalmoscope, a simple optical device for viewing the inside of the eye. At UCSD, A. Quirrenbach has constructed laser tweezers, which use light to trap microscopic dielectric particles such as cells. The tweezers are equipped with a CCD camera that provides a video display for classroom instruction. This state-of-the-art technology can demonstrate a number of physical principles and is regarded by students as relevant to their future careers (e.g., biological samples). The lab exercises will be tested both at Rochester in collaboration with T. Erdogan and at UCSD. Following testing and revision, they will be made available to undergraduate physics teachers by placing them on the Web and publishing them in journals such as Physics Today and/or Optics and Photonics News.

3.5.2: Career Management Series The Career Management Series (CMS) is designed to help young researchers with guidance and information regarding career choices based on their individual interests and values. The series offers in-depth information regarding academic and private sector job searches and provides communication training useful to both sectors. The workshop, *Developing Scientific Leadership*, was presented March 15-17 in collaboration with the Center for Particle Astrophysics (CfPA). It offered science postdocs a framework for identifying effective management and leadership perspectives and engaged them in an intensive set of communication skill building exercises, explored the ethical relationship between science and society, and provided a forum for self-exploration of personal values and principles. The workshop was attended by 25 postdoctoral researchers representing the fields of physics, astronomy, astrophysics, ecology and biotechnology. Senior members of the scientific community participated in the development and presentation of the materials, and acted as mentors/participants throughout the three-day gathering. Participants' responses to an exit questionnaire were uniformly enthusiastic in their evaluation of the workshop. The CfAO plans to host another workshop in the winter of 2001, probably centered on Non Academic Careers, with the plan of transporting it one or two other CfAO sites.

3.5.3 Chautauqua This summer the CfAO organized a Chautauqua short course titled, *The Sharper Image: Adaptive Optics in Astronomy & Vision Science*. A Chautauqua course is aimed at participants who are experts in classroom instruction and is an excellent vehicle to directly integrate Center research into undergraduate curricula - an expressed goal of the NSF sponsored Chautauqua program. *The Sharper Image* was held at Yerkes Observatory June 20-23. The ten participants were given a solid background in the theory and practice of adaptive optics and its applications in the fields of astrophysics and vision science, for example the use of AO imaging to identify the distribution of individual color photoreceptors in a living human eye. Associated labs provided opportunities to experiment with AO systems and Image Processing (e.g., determining the diffraction limit of one’s eye). An additional outcome of this short course was the development of a number of laboratory/demonstrations related to adaptive optics, which will have broader applications. For example "Lucky Shot" which combines a small telescope a video camera and a frame grabber to dramatically illustrate the importance and need for AO.

3.6 General Public/Life Long Learners:

Astronomy, vision science, and the dramatic visual images that have resulted from the use of adaptive optics are the source of considerable public interest. The center reaches this audience through lectures and observatory visits, electronic media, print media (e.g., January cover story of Physics Today) and our collaborations with museums and planetaria. The CfAO web site is still in a formative stage, but will become another resource for promulgating information as it will contain images of our research and resources for students and educators. CfAO has cultivated partnerships with Adler Planetarium in Chicago, Chabot Space & Science Center in Oakland, the Exploratorium in San Francisco and the Hayden Planetarium in New York. While we are collaborating with Adler and Chabot on our precollege programs, more importantly all four institutions have expressed interest in creating exhibits based on Center research. Adler is currently developing an exhibit for the Milky Way gallery based on A. Ghez's discovery of a black hole in our galaxy. Other potential projects include developing a simple AO demonstration with the Exploratorium, which specializes in hands on exhibits and perception, and providing images and content for new multi-media "cyber-cafés" at Adler, Hayden and Chabot. For example exciting new images of the cones in a human retina or of an astronomical discovery could be rapidly displayed on "electronic bulletin boards", computer generated, high resolution, large format, video displays; and distant groups can be linked to scientific experts via video conferencing and other distance learning technologies (e.g., web-casts). The Center is well poised to contribute content to these major technological investments being made by our partners.

3.7 Looking Towards the Future:

While the initiatives we have implemented are taking root, our long term goal is to integrate them into a seamless matrix with links between the programs. An educational retreat is planned for the early fall, which will involve *all* the educational stakeholders. The goal is to identify interconnections among current programs and to articulate a clear vision for the Center. It is critical that center scientists help in the formulation of this vision to ensure that they participate in future outreach efforts. Subsequent funding appropriations will take into account project cross linkages and researcher involvement. In addition to this broad goal of unifying and focusing our outreach efforts, we have a number of specific plans for the upcoming year as follows.

In 2001, the center intends to offer a national, summer, REU program that specifically targets women and underrepresented minorities. The goal is to involve 15-30 undergraduate students. The advantages of a centralized CfAO REU approach relative to those available through participating institutions, includes, potential improvements in student recruiting, supervision, evaluation, tracking, and project design. The CfAO internal criteria will give preference to requests that include: the recruitment and involvement of underrepresented groups, meaningful research projects, and plans for student-faculty interaction. The CfAO is also endeavoring to establish research partnerships with Historically Black Colleges and Universities (HBCU) with the aim of encouraging their undergraduates to enter our summer programs and later to return as graduate students. As a first step, through existing contacts, we will target HBCU faculty with the advertisement for the CfAO summer women and minority REU program.

In summary, the CfAO's education and outreach efforts are off to an exciting start. We are providing opportunities to many under-served K-12 students, have created a mechanism that ensures the active participation of Center scientists, and have established multiple dissemination mechanisms for our outreach and our science (e.g., NSTA, HOU, Adler & Chabot).

4. Outreach and Knowledge Transfer

Industrial partnerships within the CfAO are currently concentrated in three areas: vision science, micro-electro-mechanical systems (MEMS), and lasers. Other areas of partnership activity include support of existing astronomical AO systems, design of AO systems for giant telescopes, software for AO users, and detectors.

4.1 Vision Science

In the area of vision science there are two active industrial partnerships. The first is with Bausch and Lomb who are working on a variety of topics with the CfAO vision science nodes, particularly the University of Rochester. These include development of commercial technology for sensing the wavefront aberrations of the human eye, measurement of population statistics for the wavefront aberrations of the eye, and development of commercial adaptive optics instrumentation for the correction of high-order aberrations of the eye. In addition, B&L are co-sponsoring a University of Rochester vision science post-doctoral fellow and have joined the Alliance for Visual Excellence at the University of Rochester.

On the topic of development of commercial technology for sensing the wavefront aberrations of the human eye, Technolas, a German laser eye surgery company and subsidiary of B&L, has used techniques, developed at the University of Rochester and licensed to B&L, in the production of a commercial wavefront sensor. This wavefront sensor is commercially available in Europe, and was demonstrated at the meeting of the American Society of Cataract and Refractive Surgery in Boston in May 2000. The University of Rochester has continued to work with B&L and Technolas on the development and testing of this instrument.

Regarding the measurement of population statistics for the wavefront aberrations of the eye, the CfAO vision science nodes have worked with B&L to collect data on a number of subjects. Results from one sample are shown in Figure 13 These show that, on average, 17% of the wavefront aberrations of the eye are at higher spatial frequency than the aberrations of defocus and astigmatism, which can be corrected by conventional eyewear or refractive surgery. These population statistics feed back into the Center work on next-generation vision-science systems, as described under Goal 3.

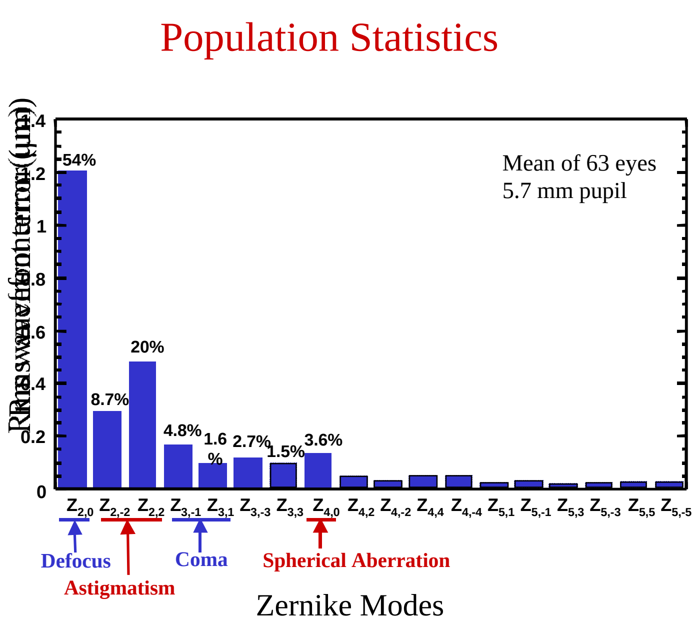


Figure 13: Measurements of aberrations in a representative population of human eyes. Only the defocus and astigmatism terms can be easily corrected by conventional techniques.

On the topic of development of commercial adaptive optics instrumentation for the correction of high-order aberrations of the eye, discussions have begun between B&L, the University of Rochester and the other CfAO vision science nodes, along with LLNL. These seek to formulate a strategy for development of this instrumentation. Ophthalmologists from, for example, Johns Hopkins University and the University of California, Davis have expressed interest in working with the CfAO to test prototype instruments, and a strategy for participation of the ophthalmology community in such tests is being developed.

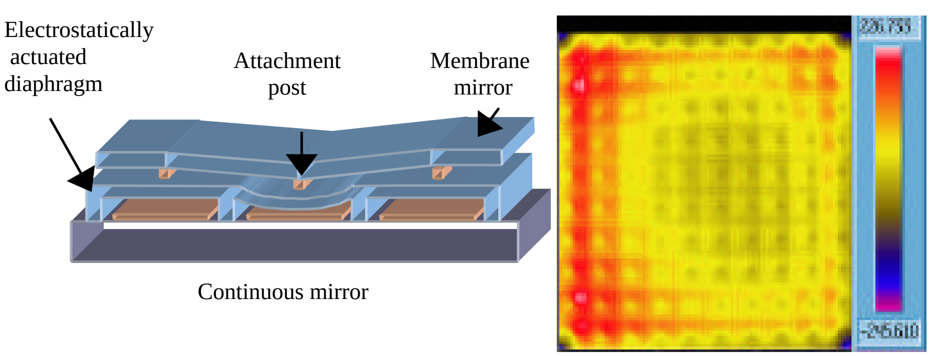
Other companies, for example, Zeiss-Humphrey Systems, have also expressed interest in working with CfAO institutions on the development of commercial adaptive optics instrumentation for the correction of high-order aberrations of the eye. In response to this interest, and following suggestions by the Program Advisory Committee and the External Advisory Board, a CfAO committee on industrial partnerships has been convened to review the Center industrial partnership policy. This committee will evaluate policy particularly with regard to the intensely competitive commercial environment surrounding the development of ophthalmic instrumentation utilizing adaptive optics technology, and the intellectual property rights of the CfAO institutions and industrial partners. An initial report is due in October 2000.

The second industrial partnership in the vision science area is with the Environmental Research Institute of Michigan (ERIM). This is focused on sensing the wavefront aberrations of the eye using the technique of phase diverse phase retrieval. This method of wavefront sensing, in which ERIM is a world leader, has potential advantages over the conventional Hartmann sensing method. In particular, the optical system required for this method could be simpler, which would be advantageous for a commercial instrument. This partnership involves a graduate student at the University of Rochester and has recently begun to achieve interesting results and additional work will be carried out through the end of the fiscal year. Such techniques have a long history of use in astronomy but may in fact be even better suited to the complex but relatively static aberrations encountered in the human eye.

4.2 Micro-electro-mechanical systems

In the area of MEMS, there are also two active industrial partnerships. The first is with Lucent Technologies and involves a post-doc at the University of California, Berkeley who will be resident at Bell Labs in Murray Hill, NJ. The focus of this partnership is to utilize the MEMS packaging and drive electronics technology developed by Lucent. This technology, which has been developed for an optical cross-connect switch product line at Lucent, will be used in the CfAO for the MEMS deformable mirrors being developed by other CfAO institutions and partner organizations. A secondary goal will be to utilize new MEMS fabrication process technology being developed at Lucent for single crystal silicon in order to produce a new type of MEMS deformable mirror device with improved characteristics compared with devices currently under development using existing surface micro-machining foundry processes.

The second industrial partnership in the area of MEMS is with Boston Micromachines Corporation (BMC). This start-up company is a spin-off from Boston University (BU) that is commercializing the MEMS deformable mirrors developed there. BMC and BU have recently made a breakthrough in the post-processing of MEMS mirrors that enables the consistent production of optically flat surfaces. Other CfAO partner institutions, particularly LLNL, with the participation of a graduate student from the UC Davis branch of the Berkeley Sensor and Actuator Center (BSAC), are now working closely



Mirror surface map

Figure 14: Schematic (left) and surface phase image (right) of BU MEMS 144 element deformable mirror. The standard deviation of the surface phase map is ~50 nm.

with BMC and BU to characterize the MEMS deformable mirrors they have produced. A schematic and an interferometric phase map of this device is shown in Figure 14.

Along with the industrial partners, several other partner institutions are also active in the MEMS area. First, 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 and in the investigation of 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. Second, the Air Force Research Lab (AFRL) at Wright-Patterson Air Force Base has been active in the design of MEMS deformable mirrors to meet CfAO requirements. These devices are currently in fabrication in the MEMS foundry facility at Sandia National Laboratory (SNL). The final partner institution in this area, The Lawrence Livermore National Laboratory (LLNL) has been responsible for the coordination of the CfAO MEMS development activities. This coordination has included the organization of a CfAO MEMS development kickoff meeting in November 1999, and the subsequent drafting of the overall CfAO MEMS development plan based on the recommendations of the participants at the kickoff meeting. LLNL has also collaborated with BSAC in the development of techniques for bonding mirror and actuator arrays. LLNL has collaborated with AFRL and Lucent in the design of the AFRL MEMS deformable mirror and the design of a sub-mount for the packaging of this device at Lucent. LLNL is collaborating with BSAC in the characterization of the BU/BMC MEMS deformable mirror, and plans to continue this collaboration to characterize the AFRL device later this year. LLNL will also conduct complete performance evaluation of these devices in its laboratory adaptive optics test bed.

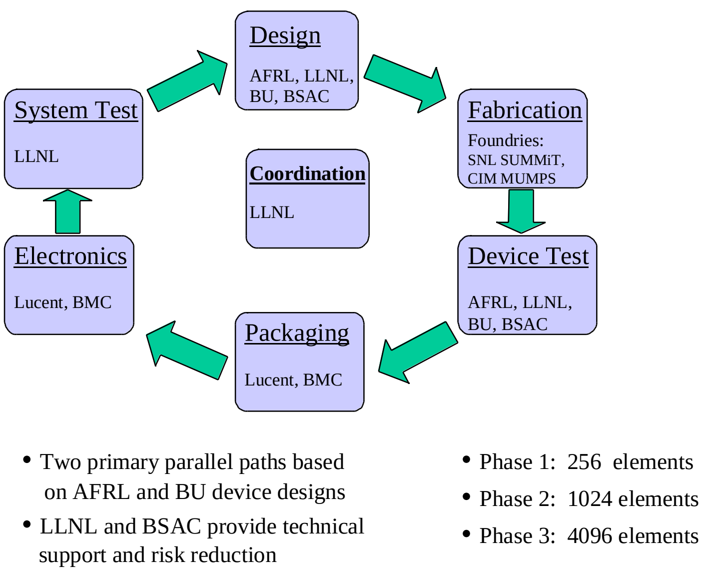


Figure 15: Flowchart of MEMS development/test process

Figure 15 shows the overall organization of the consortium of institutions participating in the CfAO MEMS development plan. In the first year, there are two parallel development paths expected to produce working devices. These paths are based on designs by BU and AFRL, which were already developed through several generations prior to the start of the CfAO. These designs utilize publicly available foundry fabrication facilities at SNL (AFRL design) and Cronos Integrated Microsystems (CIM, BU design). Both SNL and CIM have made considerable investments in the development of fabrication processes for optical MEMS for a variety of applications including optical switching for telecommunications. After fabrication and initial inspection, the CfAO plan calls for these devices to be packaged and integrated with drive electronics at Lucent Technologies, based on their infrastructure developed in support of their commercial optical switching products. Additional support for packaging and drive electronics will be provided by BMC. The packaged MEMS device assemblies will then be evaluated in an adaptive optics test-bed at LLNL. In addition to the BU and AFRL devices, a third effort is ongoing at BSAC, as discussed under Goal 4.

4.3 Lasers

In the area of lasers for the production of sodium beacons for astronomical AO, one of the CfAO partner institutions, the Gemini Telescope Project, has been active in co-funding and coordinating laser development. Gemini organized a laser development planning meeting in December 1999 that including participation by the NSF and the European Southern Observatory. These activities have lead to direct interactions with two companies, Lite Cycles and Coherent, and another partner institution, the AFRL at Kirtland Air Force Base who is working with another company, LightWave Electronics.

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 advanced solid-state laser designs. In the next fiscal year, LLNL is planning to explore fiber lasers and work with Stanford University on new sum-frequency conversion methods.

4.4 Other partnership activities

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.

Design of AO systems for giant telescopes: NOAO has co-sponsored a working group with the CfAO to produce a national 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. The Gemini Telescope Project has also produced a thorough conceptual design of a multi-conjugate adaptive optics system that could dramatically increase the AO corrected field size.

Software for AO users: the CfAO organized a meeting that was attended by NOAO and the European Southern Observatory. As a partner institution, NOAO is planning to work with UC San Diego in the development of astronomical AO software tools.

Detectors for AO: the CfAO sponsored a meeting that was attended by several companies including Rockwell Science Center, a CfAO industrial partner that is developing detector technologies that may enable IR wavefront sensing for astronomy. Rockwell is also working with UCLA on detectors for IR astronomical imaging cameras.

5. Shared Experimental Facilities

5.1 Astronomical AO systems:

Center members are responsible for the operation of three major adaptive optics facilities described below – the Lick AO system with its laser guide star, the Palomar AO system, and the ChAOS laser AO system. In addition to these, Center members are users of several other astronomical AO systems, most notably the AO system on the 10-m W.M. Keck telescope, currently the most powerful astronomical AO system in the world. Access to these facilities is governed by the telescope time allocation rules of the institutions that own the telescopes; generally they are available to all astronomers at their respective member institutions, which (through Keck, Lick, Palomar, and ARC) encompass a substantial fraction of the US observational astronomical community.

<u>5.1.1: Lick Observatory Adaptive Optics System</u>: The prototype laser guide star adaptive optics system was developed for the Lick Observatory 3-m Shane Telescope by LLNL. The system uses a 127-actuator deformable mirror and a 20-watt dye laser. Since Lick is conveniently located near LLNL and UCSC, and since large amounts of telescope time (20-30 nights per semester) are available on this

telescope for this project, this Lick system is an excellent testbed for developing laser guide star techniques and experimenting with advanced concepts such as multiple laser beacons. In addition, the 3-m telescope provides a good facility for younger Center members (postdocs and students) with limited Keck access to try out concepts for AO science programs. Lick Observatory generally has good seeing (<0.8" at 2 microns) for much of the summer and fall. IRCAL, a near-infrared 1-2.5 micron science camera developed by Prof. James Graham (UC Berkeley), with spectroscopic capability, is used for science observations.

5.1.2: Mt. Palomar Adaptive Optics System: The Palomar Adaptive Optics System (PALAO) is a 241-actuator AO system on the 5-m telescope on Palomar Mountain. This is a facility instrument funded by JPL. It feeds a dedicated infrared AO science camera for high-resolution coronagraphic imaging and moderate-resolution spectroscopy. The system will be initially natural-guide-star based, with development of a laser guide star to proceed based on the Center's studies of laser concepts. The system will be available to the Center's JPL and Caltech members and to outsiders through collaborative proposals and will be used primarily for AO science observations.

5.1.3: ChAOS Adaptive Optics System: ChAOS is a facility laser guide star AO system being installed on the 3.5-m ARC telescope in New Mexico, funded by separate NSF grant. It will be used for science observations and AO technology development, in particular studies of laser systems and reconstructor algorithms. It includes a sum-frequency solid-state sodium laser beacon that is being upgraded through the Center

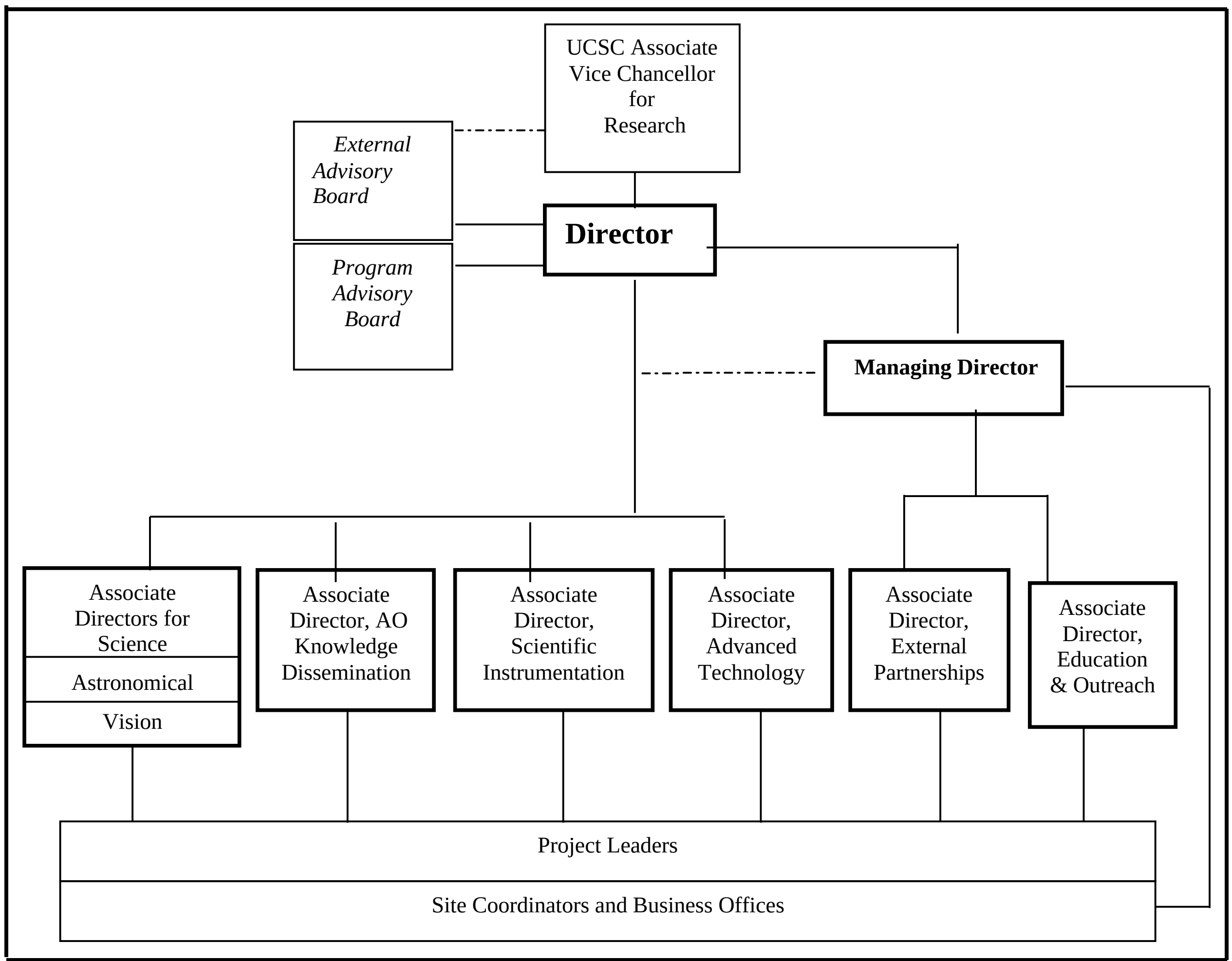
5.2: Vision Science AO systems:

Currently, the Rochester adaptive optics instrument, completed in 1996, is the only functioning AO system for the human eye. Its expense and complexity limits its widespread development and use. A goal of the Center is to develop two shared adaptive optics systems that will make this technology accessible to a larger community of basic visual scientists, research optometrists, and research ophthalmologists in academia and industry.

Scientists will apply to use these shared facilities, and a committee consisting of the three principal investigators from Rochester, Houston, and Indiana (Williams, Roorda, and Miller) will evaluate the request. Each applicant will be expected to provide their own support (from NIH, for example) for the experiments performed including any expense of modifying the instrument to meet their specific needs. The Center will provide salary support for an engineer at each site to maintain each instrument.

6. Administration and Management

6.1 Organizational Chart



6.2 Management Responsibilities

The organizational chart schematically depicts the CfAO management structure, central to which is a strong executive function.

The Director is also the Chief Scientist, he has overall responsibility for the Center activities and the prime responsibility for all research activity within the Center. All reporting to the Director is done through the Managing Director.

The Managing Director is responsible for all outreach and business aspects of the Center's operation. He has the fiscal responsibility for the research budgets.

The Executive Committee – This is made up of the Director, Dr. Jerry Nelson; the Managing Director Dr. Chris Le Maistre, Associate Directors and Site Coordinators.

Associate Directors

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 Outreach, Randy Landsberg (Acting);
External Partnerships, Dr. Scot Olivier*;*
Associate Director at Large, Dr. Bernard Sadoulet

Site Coordinators (who are not also Associate Directors)

Michael Brown	Caltech
Gary Chanan	University of California, Irvine
Sandra Faber	University of California, Santa Cruz.
James Graham	University of California, Berkley
Ed Kibblewhite	University of Chicago
Austin Roorda	University of Houston
Don Miller	Indiana University

The Executive Committee receives advice from the External Advisory Board (EAB).

6.3 Major Center Issues and Proposed Solutions

6.3.1 Research***:*** The research has been organized into five functional activities or goals. Some research projects cross over goals. However in the main, the Associate Director of each goal is responsible for over-viewing and evaluating the ongoing research of the projects within the goal and the required reporting. The Associate Directors also advise the Director on the viability of the research being done within the goal, on a project by project basis and the proposed level of funding if the research is to be continued. The Associate Directors and their relevant goals are listed above.
Before the pending research agenda is approved, it is presented to an external Program Advisory Committee for their comment. The Director makes the final decision on all proposed research.

6.3.2 Business and Outreach***:*** The Managing Director is responsible for the operational functions of the Center. Functions that report to or are coordinated by the Managing Director are the site business offices, information networks, external partnerships and educational outreach and other activities associated with knowledge transfer including patents and licensing. The Associate directors of External partnerships and educational outreach are members of the Center's Executive Committee. They interact with the research and technology groups so ensuring that the outreach programs are compatible with these activities and build on their strengths.

6.3.3 Current Issues: The CfAO issues have centered around those associated with the start of a new center – staffing and the establishment of a research agenda. The Managing Director has recently taken up his appointment and an Associate Director for Educational Programs and Outreach (EPO) should be appointed in the near future. Both external advisory committees, while endorsing the quality of the research undertaken and the results obtained, have commented on the number and diversity of the research projects and the need to coordinate and manage them. The Executive Committee is sensitive to these issues and is closely monitoring current projects. Similarly, there is a wide diversity in the Educational programs being supported. It is anticipated that an Associate Director for Educational programs will be hired shortly and that with this and the planned Center EPO workshop in the fall, some consolidation and alignment of the educational programs with Center goals will be established.

6.4: Membership of Advisory Committees

The External Advisory Board (EAB) has representatives from the fields of Astronomy, Adaptive Optics and Education. They provide overall advice on the research and policies of the Center. Members of the External Advisory Board are:

Dr. Pablo Artal
Universidad de Murcia, Spain
Campus de Espinardo (Edificio C)
30071 Murcia
Spain

Dr. Chris Dainty
Imperial College, London
Blackett Laoratory
London, UK SW7 2BZ

Dr. Goery Delacote
The Exploratorium
3601 Lyon Street
San Francisco, CA 94123

Dr. Robert Fugate
Starfire Optical Range
3550 Aberdeen Ave., SW
Alburquerque, NM 87117-5776

Dr. Thomas Jeys
MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02

Dr. Robert Kirschner
Harvard-Smithsonian, CfA
60 Garden St. MS 19
Cambridge, MA 02138

Dr. Harold MacAlister
Georgia State University
1 Park Place South SE #700
Atlanta, GA 30303

Dr. Matthew Mountain
Gemini Observatory
670 N A"ohoku Place
Hilo, HI 96720

Dr. Maria Santos
San Francisco Unified School District
2550 25th Avenue
San Francisco, CA 94116

Dr. Allan Wirth
Adaptive Optics Associates, Onc.
10 Wilson Road
Cambridge MA 02138

Dr. Sidney Wolff (Chair)
National Optical Astronomy Observatories
PO Box 26732
Tucson, AZ 85726

The Program Advisory Committee (PAC) provides their advice and insights into the research being pursued, both within and outside of the CfAO. Members of this committee are as follows:

Dr. James Belectic (Chair)
W. M. Keck Observatory
65-1120 Mamalahoa Highway
Kamuela, HI 96743

Dr. Mike Bolte (temporary for yr 2000)
University of California, Santa Cruz
1156 High Street
Santa Cruz, CA 95064

Dr. Mark Colavita
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109

Dr. Francisco Hernandez
University of California, Santa Cruz
1156 High Street
Santa Cruz, CA 95064

Dr. Joyce Justus
University of California, Santa Cruz
1156 High Street
Santa Cruz, CA 95064

Dr. Stanley Klein
University of California, Berkeley
420 Minor Hall
Berkeley, CA 94720

Dr. Anneila Sargent
California Institute of Technology
1201 East California Blvd.
Pasadena, CA 91125

Dr. Steve Vogt
University of California, Santa Cruz
156 High Street
Santa Cruz, CA 95064

Appendices

Appendix A: List of Center Publications, November 1999-June 2000

1. Applegate, R.A. , L.N. Thibos, A. Bradley, S. Marcos, A. Roorda, T.O. Salmon, and D.A. Atchison. "Reference axis selection: A subcommittee report of the working group to establish standards for the measurement and reporting of the optical aberration of the eye," Vision Science and its Applications: Technical Digest (OSA, Washington, D.C.) , 146-149. 2000.

2. Bloemhof, E. E., Marsh, K. A., Dekany, R. G., Troy, M., Marshall, J., Oppenheimer, B. R., Stability of the adaptive-optic point-spread function: metrics, deconvolution, and initial Palomar results, Proc. SPIE, 4007, (2000).

3. Bloemhof, E. E., Oppenheimer, B. R., Dekany, R. G., Troy, M., Hayward, T. L., Brandl, B., Studies of Herbig-Haro objects with the Palomar adaptive optics system, Proc. SPIE, 4007, (2000).

4. Brainard, D.H. , A. Roorda, Y. Yamaguchi, J.B. Calderone, A.B. Metha, M. Neitz, J. Neitz, D. R. Williams, and G. H. Jacobs. "Functional consequences of individual variation in relative L and M cone numerosity," J.Opt.Soc.Am.A 17(3), 607-614. 2000.

5. Chanan, Gary and Mitchell Troy, "Strehl Ratio and Modulation Transfer Function for Segmented Mirror Telescopes as Functions of Segment Phase Error," Applied Optics, Volume 38, pp. 6642-6647 (November 1, 1999).

6. Dekany, R. G., Banfield, D. J., Bouchez, A., Oppenheimer, B. R., Brown, M., Hayward, T., Brandl, B., Troy, M., Brack, G., Shi, F., Trinh, T., Solar system science with subarcsecond slit spectroscopy , Proc. SPIE, 4007, (2000).

7. Dekany, R., G., Troy, M., Ealey, M., DuVarney, R. C., Bleau, C. A., Brack, G., Trinh, T., Shi, F., Palmer, D., 1600 actuator tweeter mirror upgrade for the Palomar adaptive optics system (PALAO), Proc. SPIE, 4007, (2000).

8. Ge, J., Ciarlo, D., Kuzmenko, P., Macintosh, B., Alcock, C., Cook, K., Gavel, D., Max, C., Lloyd, J., Graham, J., Liu, M., Severson, S. 1999, BAAS, 195, 8715

9. Larkin, J. E., & Glassman, T. M. 1999 "Faint Field Galaxies Around Bright Stars: A New Strategy for Imaging at the Diffraction Limit", Publications of the Astronomical Society of the Pacific, 111, 1410.

10. Lloyd, J. P., Liu, M. C., Macintosh, B. A., Severson, S. A., Deich, W. T. S., Graham, J. R., IRCAL: The Infrared Camera for Adaptive Optics at Lick Observatory, Proc SPIE 4008 (in press)

11. Marshall, J., Troy, M., Dekany, R. G., Anisoplanicity studies within NGC6871, Proc. SPIE, 4007, (2000).

12. Martin, E.L. , C.D. Koresko, S.R. Kulkarni, B.F. Lane, P.L. Wizinowich (2000) ApJL, 529, 37 "The Discovery of a Companion to the Very Cool Dwarf Gliese 569B with the Keck Adaptive Optics Facility"

13. Max, C., Macintosh, B., Gibbard, S., Roe, H., de Pater, I., Ghez, A., Acton, S., Wizinowich, P., Lai, O., “Adaptive optics imaging of Neptune and Titan”, BAAS 195, 93.02’

14. Miller, Donald T. , “Retinal imaging and vision at the frontiers of adaptive optics,” Physics Today, 31-36 (January 2000).

15. Oppenheimer, B. R., Dekany, R. G., Troy, M., Hayward, T. L., Brandl, B., Companion detection limits with adaptive optics coronagraphy, Proc. SPIE, 4007, (2000).

16. Prato, L., Ghez, A. M., Pina, R. K., Telesco, C. M., Fisher, R. S., Wizinowich, P., Lai, O., Acton, S., and Stomski, P. 2000 ``Warm Circumbinary Dust in the HD 98800 Quadruple System," in IAU 200 "Binary Star Formation" Poster Book Proceedings

17. Quirrenbach, A., Lai, O., Larkin, J., Neugebauer, G., Weinberger, A., & Wizinowich, P. (1999). Keck Adaptive Optics Observations of Seyfert Nuclei. BAAS 31, 1513

18. Rembe, Christian , Michael Helmbrecht, Matthew Hart, Kam Lau, Richard Muller, “Stroboscopic Interferometer with High Spatial Resolution to Measure 3D Movements in MEMS,” Synergies in Engineering Research Meeting, April 26-27, Günzburg, Germany

19. Roorda, A. and D.R. Williams. "Angular tuning of single cones in the living human eye," Invest.Ophthalmol.Vis.Sci.Supplem. 41(4), 100-100. 2000.

20. Roorda, A. and J. Neitz. "Chromatic topography of the retina," J.Opt.Soc.Am.A 17(3), 495-496. 2000.

21. Troy, M., Dekany, R. G., Oppenheimer, B. R., Brack, G., Shi, F., Bloemhof, E. E., Trinh, T., Dekens, F., Palomar adaptive optics project: status and performance, Proc. SPIE, 4007, (2000).

22. Williams, D.R. and A. Roorda, "The trichromatic cone mosaic in the human eye," in Color Vision: From Geners to Perception, K. R. Gegenfurtner and L.T. Sharpe, eds. (Cambridge University Press, Cambridge, 2000). pp. 113-122.

23. Williams, David R. , Junzhong Liang, Donald T. Miller, and Austin Roorda, Wavefront Sensing and Compensation for the Human Eye, Chapter in Adaptive Optics Engineering Handbook, ed. R. K. Tyson, Marcel Dekker, New York (2000).

24. Wilson, B.J. , K.E. Decker, and A. Roorda. "Monochromatic aberration provide an odd-error cue to focus direction," Invest.Ophthalmol.Vis.Sci.Supplem. 41(4), 427-427. 2000.

25. Wizinowich, P., Acton, D., Shelton, C., Stomski, P., Gathright, J., Ho, K., Lupton, W., Tsubota, K., Lai, O. Max, C., Brase, J., An, J., Avicola, K., Olivier, S., Gavel, D., Macintosh, B., Ghez, A., Larkin, J., “First Light Adaptive Optics Images from the Keck II Telescope: A New Era of High Angular Resolution Imagery”, 2000 PASP 112, pg 315

26. Yamauchi, Y. , D.R. Williams, D. Brainard, J.B. Calderone, A. Roorda, M. Neitz, J. Neitz, and G. H. Jacobs. "Is unique yellow determined by the relative numbers of L and M cones?," Invest.Ophthalmol.Vis.Sci.Supplem. 41(4), 526-526. 2000.

Appendix A (continued.)

Intellectual Property:

The Center had no patents, filings or disclosures reported in the first year.

Appendix B: M.S and Ph.D. Placements

Postdoctoral Investigators:

Name	From	To
Luc Simard	UCSC	University of Arizona

Appendix C: Center Participants

See following pages (A14-A15)

Appendix D: New Investigator Biographies

No new investigators added

Appendix E: Awards and Honors:

Principal Investigators:

Austin Roorda: Founders Wavefront Award for best talk at the "First International Conference on Wavefront Sensing and Aberration-free Refractive Correction." Santa Fe, NM, February, 2000

Postdoctoral and Graduate Students

None reported.

Appendix F: Report of the External Advisory Board

June 2000

Executive Summary

The Center for Adaptive Optics (CfAO) is off to a strong start. In operation for only about six months, the Center has assembled a very strong team of astronomers and vision scientists, allocated funding for a diverse set of projects, achieved impressive experimental results, and established partnerships with a number of programs in education and public outreach.

The program of the CfAO has four primary goals: 1) the support of forefront science enabled by the use of AO; 2) the dissemination of AO tools to the community of users outside the Center; 3) the building of new science instrumentation optimized for AO; and 4) the building of advanced AO systems that offer new capabilities. The current focus of the program is on the first two goals, an appropriate strategy given that first generation AO systems are just now becoming mature enough to be used for a variety of applications in astronomy and vision science.

Over time, the Center program is likely to evolve toward greater emphasis on the third and fourth goals. An evolution in emphasis will probably require an evolution in the staffing of the center and changes in the mix of supported programs. To facilitate that evolution, the External Advisory Board (EAB) recommends that a timeline be developed for the CfAO as a whole, with measurable milestones for the Center in addition to the milestones already established for currently funded individual projects.

The External Advisory Board offers the following specific recommendations:

- It is urgent that the leadership positions of Deputy Director of the CfAO and Associate Director for Education and Outreach be filled. These two key staff, along with the other Associate Directors, have critical roles to play in overseeing the many projects already under way and in streamlining the management of the Center.
- The CfAO should establish as early as possible the metrics by which the degree of success of both its scientific and educational programs will be evaluated.
- A road map needs to be designed that describes the process for translating software developed in service of individual projects into a form that can be used by the broader AO community.
- The intellectual property regulations should be reviewed by legal counsel to ensure a proper balance between the requirements of the industrial partners and the desire of the AO scientific community for open and free interchange.
- It is essential to monitor the work of AO groups outside the Center to ensure that the CfAO targets its investments toward areas that will have the most significant impact.

Pablo Artal
Tom Jeys
Robert Kirshner
Hal McAlister
Sidney Wolff (chair)

I. Introduction

The External Advisory Board of the Center for Adaptive Optics met in Santa Cruz on May 30 and 31. This was the first meeting of the EAB, which heard a series of well prepared presentations that described the achievements of the CfAO to date, identified the issues currently being addressed, and laid out some of the plans for future projects.

Overall, EAB members were very impressed with what has been accomplished during the six months that the CfAO has been in operation. A number of important scientific results had been achieved with the adaptive optics system currently operating on the Keck telescope, and these early results offered a clear demonstration of the fact that AO is maturing to the point where it can be used to address important astrophysical questions. The Center programs in astronomy have been designed to address challenging observational problems that stress both instrumentation and data reduction techniques: high contrast imaging, crowded field photometry and astrometry, and measurements of bright extended objects. This work has already achieved some superlatives: faintest companion, faintest galaxy, and faintest galactic center sources detected with AO. The ultimate goal of high-contrast imaging will be to image planets around nearby stars. The work on faint galaxies is breaking new ground, and AO imaging has quantified the properties of the black hole at the center of our Galaxy.

In visual optics, Center staff have used wavefront correction techniques to conduct pioneering studies of population statistics of the aberrations of the human eye and to characterize the alignment of human cone photoreceptors.

The Center has initiated partnerships with several existing educational programs for K-12 students and with teacher enhancement efforts. Center participants were enthusiastic about this component of the overall program and are strongly committed to it. The CfAO has also sponsored six workshops for Center participants and outside researchers in both vision science and astronomy and have held one internal retreat.

It is already clear that the Center has brought together many talented individuals, and the EAB saw evidence that they are working together as a coherent team.

II. Operations of the Center for Adaptive Optics

Mission of the CfAO

Adaptive Optics promises to revolutionize astronomy and have a large impact on vision science. Progress toward this promise is slowed by the fragmented and redundant efforts of many independent groups that are working to develop adaptive optics. In addition, there are some current technological problems (e.g., laser development) and future technology problems (e.g. AO for a 30-m telescope) that will require focused efforts beyond the capabilities of traditional individual research projects.

The mission of the Center for Adaptive Optics is to focus the efforts of the adaptive optics community in order to accelerate the development of a mature adaptive optics technology and make practical adaptive optics technology available for a wide array of applications within astronomy, vision science, and other fields. In order to meet this general mission the Center has set up several general goals. These are:

1. The support of forefront astronomical and vision science utilizing adaptive optics.
2. The dissemination of adaptive optics knowledge and tools to the broad US community.

3. The building of new science instrumentation optimized for adaptive optics.
4. The building of advanced adaptive optics systems with major new capabilities.

In addition to these goals for adaptive optics, the Center is committed to public science education and will devote significant resources to this area.

The mechanisms that the Center will use to reach its general goals and to carry out its commitment to education are to: a) enlist the participation of a large portion of the US adaptive optics community in activities of the Center; b) foster communication and collaboration among Center members as well as with the outside community; c) fund the development of individual adaptive optics projects within the broader context of the mission of the Center; and d) support innovative and effective community education programs.

Metrics

The CfAO needs to enunciate clearly the measures it will use to determine whether it has attained the general goals and fulfilled its commitment to education. It is very important that the yardstick of success be made clear at the beginning of Center activities. The forced acknowledgement of the means by which the Center and individual project investigators will be judged will itself sharpen the goals of the Center and may even lead to a modification of the present goals, the inclusion of different goals, or the adoption of different implementation strategies.

Milestones already exist for the individual projects being supported by the CfAO. The EAB strongly recommends that a timetable, including measurable milestones, be drafted for the achievement of the ***Center's*** goals. A well-considered timetable should extend for at least five years. A visionary timetable should extend for an additional five years. The construction of these timetables and milestones will further focus the Center and its members on these goals.

The timetable for the Center should make evident the possible evolution of the Center's goals. Such evolution is inevitable since adaptive optics is a rapidly developing field. In broad outline, such evolution is likely to include an emphasis on the first and second goals during the early years of Center operations, with the emphasis shifting to the third and fourth goals later in the program. (Currently, approximately 50 percent of the available funding is divided nearly equally between the first and second goals, with the remaining funding being allocated in nearly equal thirds to the remaining two goals and to outreach programs.) Adaptive optics systems are just now becoming available as facility class instruments to the US astronomical community and in vision science laboratories. In order to exploit these new instruments fully, it will be necessary to develop observing strategies and reduction packages, and disseminate that information to the scientific community. Later in the lifetime of the Center, it will become appropriate to explore the technologies for second-generation instruments and to begin exploration of the issues associated with building an AO system for a very large (30-m) ground-based telescope.

At a minimum, annual meetings of the Center management and the External Advisory Board should be held to assess the Center's progress towards meeting the milestones projected within the timetable.

Because the Center is not the only organization developing adaptive optics technology, it is important for the Center to track its role within the global AO community. The close monitoring of other adaptive optics efforts will allow the Center to judge where it can make the most important contributions and whether the Center's projects, goals, milestones, and timetable need modification.

Management

As part of monitoring the progress of the Center toward meeting its goals, the overall management, and the management of the individual member projects, need to be carefully considered. Clearly one of the most urgent management problems is the hiring of a Deputy Director. This has to date proved difficult. If the near-term efforts fail, the Center is encouraged to work with the University administration to redefine the level or category of the appointment. A higher level of responsibility or compensation may attract the type of leadership that the Center needs in its Deputy Director.

A less pressing, but still important, management issue is the oversight of the individual Center projects. The CfAO needs to monitor the projects for the purpose of providing feedback and help to Project Investigators. However, with the 40 or so current projects it is not reasonable to expect that the Director or even the Deputy Director can be intimately familiar with each project. It should be the role of the Associate Directors to monitor the progress of each of the projects within their individual areas of control. The Associate Directors should be charged with the responsibility of knowing at any time the status of each project in their area. This knowledge will allow the Associate Directors to see opportunities for mutually beneficial collaboration among Center members. The Center will then probably find it useful to require the Associate Directors to report formally and in detail, perhaps quarterly, the status of each of the projects. This process should ensure that the Associate Directors are familiar with the status of projects in their area of responsibility.

The monthly technical and financial reporting for each of the Center's projects is considered too cumbersome by the Project Investigators. The EAB recommends that the required financial reporting be simplified, perhaps by requiring reports no more frequently than every three months. The technical reporting may continue to be on a monthly basis or may be made less frequent (no less than every three months), but again the requirements should be as streamlined and simplified as possible. Any problems that may have occurred to delay the project, increase its technical challenge, or exceed its budget should be highlighted.

It is important that the Project Investigators receive individual acknowledgement that their reports have been read by the appropriate Associate Director. Finally, the EAB recommends that the level of project management should fit the level of funding for each project. Smaller projects should not be required to expend the same level of reporting effort as larger projects.

III. Multidisciplinary Activities

One of the purposes of the CfAO is to encourage collaboration among visual optics scientists, optical engineers, and astronomers. This multidisciplinary collaboration is surely one of the most interesting purposes of the Center. Areas where this collaboration will be specially appropriate include software tools, opto-mechanical designs, calibration procedures, etc. However, there are also substantial differences between ophthalmic and astronomical AO. These differences are not only technical and scientific in nature, but also in the approach to instrumentation. To be practical, ophthalmic AO systems need to be compact and relatively inexpensive.

The potential applications of AO in vision science are enormous. The two main areas of application that are currently being explored in laboratories around the world are:

a) *Customized static correction of the ocular aberrations by contact lenses, intraocular lenses, or laser refractive surgery*. This involves a precise determination of the ocular aberrations and the capability of producing the desired correction. In normal subjects this may lead to an improved vision (acuity better than 20/20). In certain pathological cases with severely aberrated eyes, it would produce a dramatic improvement in vision that cannot be achieved by conventional means.
b) *High resolution ophthalmoscopes equipped with closed-loop real time AO*. These devices would enable new experiments in vision science (some of them already performed within the Center). These systems also present a potential for early diagnosis of a variety of retinal diseases.

In addition to ophthalmic applications, there are also possible related biomedical areas where this kind of AO technology could be used to solve existing problems.

Even in the early stages of the operation of the Center, the EAB sees evidence of good communication and exchange of information between vision scientists and astronomers and a genuine interest in the problems being addressed by scientists in the two different fields of research. The EAB does believe that the CfAO is in an excellent position to develop new AO systems for ocular applications. To be fully successful in achieving this difficult and challenging goal, however, it will be necessary to enhance the current collaborative programs. The exchange of information that has already taken place through workshops is surely very useful, but perhaps a step forward is required. Laboratory visits, sharing of solutions related to practical problems of alignment and calibration, and input on designs of instruments should all become part of the ongoing program. In addition, the Center should extend the collaboration in this area to other groups in the world active in ocular AO.

IV. Education and Outreach

Astronomy and vision science have great potential for attracting students to science. Astronomy and adaptively corrected images offer striking pictures, which can be adapted for experimental measurements by students of all ages. Vision science offers the opportunity to apply basic principles of optics to practical applications, including the student's own perception of the world. Atmospheric phenomena and optical effects seen in the natural world are also closely related to both astronomy and vision science.

The commitment of CfAO staff to this component of the program is genuine and enthusiastic. The CfAO has jump-started its program of education and outreach by partnering with a variety of outreach programs that already exist on the campuses of Center participants. Since these programs are well established and already built around state and national education standards and age-appropriate materials, they offer the Center a way to have an immediate impact.

When the Associate Director for Education and Outreach is hired, it will be important, as CfAO participants recognize, to bring some coherence to the efforts of the Center. The CfAO should somehow draw on its members to make unique contributions. It might be useful to identify a set of physical ideas or concepts that would provide a focus for the CfAO educational initiatives. It might be useful to develop hands-on experiments or modules that could be used by Center members when they go into the classroom and also to make these modules widely available. It might be valuable to develop visual and other materials and make them available through the Web to anyone who wants to use them.

Finally, the metrics for the success of the educational component of the Center should be established early, and the effect of the programs should be professionally evaluated. Are the programs truly effective in the classroom?

The EAB was told that each participant in the Center is expected to devote five percent of his or her time to education and outreach. We like the idea that the responsibility for this component of the CfAO program is distributed broadly, and that graduate students are expected to participate. However, not all scientists are well suited to working with pre-college students. The EAB suggests as an alternative that the overall effort in education and outreach be at the level specified, but that some individuals should devote more of their time than average if they are truly interested and capable, and others should be able to perform alternative services in place of direct involvement with pre-college education. Such alternative service might include, for example, the development of software to the point where it is well documented, user friendly, and easily disseminated.

V. Other Recommendations

Industrial Partners

The current overall policy of the Center for industrial partnership is not well defined. It is not clear what role the industrial partners are expected to play in the Center and what mutual benefits will be derived from their participation. A general recommendation is to sharpen the scope of the possible partnerships.

The potential for industrial outcomes from the Center differs for the different areas. It is in principle more important for MEMS and ophthalmic applications. It is in these areas that the Center already has established partners. These partnerships may contribute to enhancing the engineering activities of the Center.

The Center should probably have legal counsel examine the intellectual property clauses that have been adopted. The balance between open access to information, algorithms, and instrument designs developed by the Center and protection of the interests of the industrial partners needs to be clearly defined and understood in a way that meets the requirements of all the parties. For example, a conflict might arise if a researcher wanted to make available in the public domain specific AO software developed by the Center if that software also had commercial potential.

Software Road Map

The development of the software required to extract quantitative information from AO data is an extremely high priority for both the astronomical and vision science communities, and is therefore appropriately a very high priority for the Center as well. Indeed the production and distribution of well documented and reusable AO reduction and analysis software tools represent significant "deliverables" that will benefit all users of AO, whether or not they are directly associated with the CfAO. The Center clearly possesses the scientific expertise to develop these tools and has identified many of the issues that must be addressed in order to make software packages generally available. However, what was lacking at this early stage in the development of the CfAO was a plan for converting software written by individual researchers into easily transportable packages that can be readily used by uninitiated members of the community. We encourage the Center to develop a road map showing the process by which software developed as a result of the research activities of its members can be effectively transferred to the outside world. We recognize that NOAO has agreed to distribute the software, but a clear definition of the interface between CfAO and NOAO is needed. What are the coding standards and languages that will be applied to CfAO-developed software and what will be its level of completeness at the time that NOAO assumes responsibility? Is the level of effort that CfAO expects from NOAO consistent with NOAO's resource availability?

Internal Proposal Review Process

The Center has recently concluded the review of projects proposed for funding in the second year. Because most of the CfAO projects have been underway for only a few months, with all of the delays associated with hiring staff for new projects, continuation of most of the ongoing projects into the second year was an appropriate strategy and was largely the outcome of the allocation of resources. However, Center staff concluded after completion of this budgetary process that there was insufficient time to allow for a uniformly judicious review of proposals and budgets for the number of projects being supported—a problem that will only become more serious as current projects are completed and new ones proposed. Based on this experience, the Center leadership has proposed a new process that will begin each February with the Executive Committee (EC) identifying goals for the coming year and disseminating these goals to Center participants in advance of the development of individual proposals. This procedure will then allow PIs to respond to the goals in a timely manner. Proposed activities would be reviewed in the spring by the Associate Directors and the EC with final approvals coming from the Director in May. The EAB believes this revised process is a good one that will permit the development of future activities in an unrushed and thoughtful manner and will help to ensure that the individual programs are consistent with the overall goals of the CfAO.

Staffing

The EAB was asked specifically to comment on whether the staffing of the CfAO provides the right mix of expertise. There are a few areas where recruitment for key positions is ongoing, most notably the Deputy Director and the Associate Director for Education and Outreach; both positions are critical to the overall success of the Center. In the areas of both education and industrial partnerships, the goals of the program must be more clearly defined before the appropriate staffing can be determined. In the area of software, professional help may be required to translate scientist-developed packages or algorithms into broadly useful tools for AO researchers. At the present time, most of the staff hired specifically for CfAO projects are students and postdocs. Given the emphasis on the first two goals—application of AO to science and dissemination of AO tools and knowledge—this type of staff is probably appropriate. However, it is likely that the balance will have to shift more toward professionally trained engineering and technical staff if the emphasis later shifts toward the third and fourth goals—building of science instrumentation and development of advanced AO systems.

Global Links

While the Center represents a substantial portion of the US adaptive optics community, it is important that its own priorities and projects be selected to complement other related activities in the US and abroad. We encourage the Center to establish and maintain links to other AO groups (both in astronomy and vision science) and even to seek collaborations with them.

Communications

With a large membership distributed over multiple sites, the Center faces a considerable challenge in ensuring adequate communication between and among its members. For example, what is the right balance between too many and too few meetings? Who should come to meetings and who should not?

One way to avoid superfluous meetings is to keep them very topically focused with well-defined agendas, goals, and expectations for outcomes. Meetings should not in general be used as forums for announcements--such information should be posted on the Center's web site. The EAB encourages the Center to pursue its goal of identifying and utilizing video conferencing hardware to keep meeting travel to an absolute minimum. We especially encourage the ADs to use this mechanism as the primary means for carrying out bi-weekly or monthly progress reporting meetings among the projects for which they are responsible.

VI. The Legacy of the Center for Adaptive Optics

The Center is being provided with substantial resources, both financial and intellectual, over a substantial period of time. This combination gives the Center both a special responsibility and a unique opportunity to advance adaptive optics in astronomy and vision science. The EAB encourages the Center leadership to look ahead and to reflect on what they desire to be the legacy of the Center for Adaptive Optics. At its inception, the Center is wisely and appropriately following the approach of letting a "thousand flowers bloom" by supporting a diverse collection of science and technology efforts. This is appropriate since adaptive optics is just now reaching a degree of maturity that makes it possible to apply this technique to a host of challenging scientific problems.

In the end, however, it is likely that the effectiveness of the Center will be judged on a finite number of "deliverables" to the communities it is serving. These items will no doubt include scientific results that will have encouraged wider and more effective use of AO systems, but they must inevitably also include new techniques and technologies that will advance the field even farther. It is important that these deliverables bear the clearly identifiable imprint of the Center. Perhaps the greatest challenge to the leadership of the Center over the next few years will be managing the evolution from a diverse collection of PI-based projects to a more focused program aimed at the production of specific technology-oriented products.

Appendix G: Summary Report of the Program Advisory Committee (PAC)

12-14 May 2000

Participating members of the PAC:

James Beletic,	Keck Observatory, chair
Mike Bolte	UCSC
Mark Colavita	JPL
Francisco Hernandez,	UCSC
Joyce Justus	UCSC
Stanley Klein	UCB

Comments

The Program Advisory Committee (PAC) met with Center researchers on May 12 to 14, and reviewed the Center's research agenda. The following is a summary of their comments.

1. The center has a talented group of people, with a good blending of science specialties. There is a nice balance of vision science, astronomy and associated intellectual areas addressed. Exciting work was presented.

2. Overall Center.
   More focus & coordination is needed in the projects, especially the meta-projects in goals #2&4.
   There is a perceived need for researchers to have a sense of ownership and responsibility for the project.

3. Better meeting information organization
   There is a need to clarify the charter for the PAC, etc
   PAC members should receive timely information ahead of the meeting
   Keep meetings to schedule and check into possibility of a 2 days retreat.

4. Better public communication of Center activities.
   Information should be posted in Web pages/e-mail exploders, etc. Resources for this could be set aside in a Meta-project for goal #2

5. Proposal review, comments cover process and money allocation
   Process is not transparent. Process for accepting projects should be more clearly defined.
   The appearance of conflict of interest should be avoided.
   Individual projects where possible should be reorganized into meta-projects while maintaining their focus
   Metrics should be developed for evaluating on-going and proposed new projects
   The total number of projects should be evaluated re. appropriateness of the effort per project. I.e. critical mass issues.

6. Issues of intellectual property
   Amongst issues that need to be considered are industrial sponsors rights and concerns when funded research has patentable results. – need for delays in publishing etc.

7. Educational Programs and Outreach
    - Need to hire Assoc. Dir. ASAP
    - Need more focus & coordination of current programs
    - Senior management needs to set a high priority for this task.