

AN NSF-FUNDED CENTER



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Center for Adaptive Optics

Annual Report August 1, 2007

**Program Year 8
Reporting from November 1
2006 to October 31 2007**

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I. I - Contact Information and Context Statement

I.1a General Information:

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I.2 Context Statement.

The Center for Adaptive Optics (CfAO) received its initial funding on November 1st 1999. In that first year, the Center activities were grouped under: Administration, Education and Human Resources and Research. The research function was further sub-divided into four goals:

Goal 1: Science with Adaptive Optics

Vision Science

Astronomical Science

Goal 2: Bringing Adaptive Optics to the Broad Community

Goal 3: Development of Advanced Instruments for Adaptive Optics

Goal 4: Advanced Adaptive Optics.

The first NSF Site Visit was held in late September 2000 and the resultant report was critical of several aspects of the then CfAO program, including:

a. Education: The report stated “the Center must create new and innovative programs inspired by the field of adaptive optics.... the Center must be a leader rather than a follower.”

b. Research: Comments extracted from the report include:

Planning – “While the science plan for individual portions of the research is strong, there are major deficiencies in integrating the planning process into the overall structure of the Center.”

Astronomy – “The Astronomical Science has produced impressive evidence of progress” however “the plans for the review and distribution of AO-related software remains nebulous.”

Vision Science – “the work has not identified major “meta goals” that show where the long range efforts will be focused.” And “to deliver AO to the biomedical community a broader input will be required.....there is a failure in communication between the Center and other groups”

Knowledge Transfer – “It is of concern that the engineering faculty who were to be recruited were not.” And “the diversity of the Center’s participants need serious attention and could benefit from creative thinking.....the lack of a meaningful plan to attract and retain minorities is particularly striking.”

This negative evaluation by the Site Visit Committee of the CfAO’s first year led to a visit to NSF headquarters by the CfAO management team to discuss the report and conclusions. Following this visit, a decision was made to restructure the Center and to initiate the process with a two and a half day retreat of the Center’s Executive Committee on February 11 – 13th 2001 at Monterey Bay. The retreat focused on the concerns expressed at the site visit and how to re-organize the CfAO’s activities to conform more closely to the recommendations. The Executive Committee formulated a Mission Statement and proposed a new structure for the Center’s research which would be introduced to Center members at a two day Proposal Retreat on March 3-4 2001. To facilitate discussions and ensure outcomes from this event, the Center hired a strategic planning consultant.

The subsequent outcomes of this intensive strategic planning in Year 2 were that the CfAO membership developed and endorsed a statement of the Center’s mission, goals and strategies (See Section 2.1), and the reorganization of the research into Themes as follows:

Theme 1 – Education and Human Resources

Theme 2 – Adaptive Optics for Extremely Large Telescopes

Theme 3 – Extreme Adaptive Optics

Theme 4 – Adaptive Optics for Vision Science

This reorganization of the Center's education and research efforts into Themes enabled Center investigators to develop collaborative programs both within Themes and between Themes rather than work in the traditional "individual research investigator" mode. Collaborations between vision scientists and astronomers have been particularly encouraged. An extended description of the CfAO's Themes is provided in Section II.2

The new initiatives were implemented in November 2001 (Year 3), and have remained unchanged since then.

Major Developments that have occurred within the Center's Themes

The changes implemented in Year 2 relative to the management of the CfAO's science programs and their integration with the Education programs were positively reviewed by subsequent NSF site visit committees. Significant developments that have occurred within each theme over the years follow.

Education and Human Resources

The Education program held its first Professional Development Workshop (PDW) for graduate students and postdocs in Hawaii in 2001, with a focus on inquiry-based learning. The 2001 NSF site visitors saw this as a major advance, as in addition to providing young researchers instruction in modern research based teaching techniques it had increased the ties between astronomy and vision science graduate students and post-docs. In that year the CfAO summer program for minority high school students "Stars, Sight and Science" partnered with COSMOS, a University of California summer science program for high school students. Having PDW attendees act as instructors in COSMOS utilizing inquiry-based techniques in their instruction also received favorable comment.

The site visit team was very impressed with the educational programs, stating they are amongst of the strongest components of the CfAO. "It has had a profound influence on the graduate students. The Hawaiian (Maui) involvement has had key developments in the past year and has the potential to be a significant legacy for the CfAO. The professional development workshop is unique among NSF Center programs and the impact of this on the participating students is exceptional."

The success of Education and Human Resources (EHR) program led to an increase in funding for this theme from 15% to 17.5% of the CfAO budget as a result of the NSF Site Visit Committee recommendation in April 2003. In 2004 CfAO continued to extend the core elements of the program, to expand the number of people in CfAO involved in the EHR offerings, and to begin new initiatives.

Highlights presented at the 2004 review included:

- an increase in Hawaii community involvement in the professional development workshop (PDW);
- an increase (to 23) in the number of returning PDW participants who wished to assist in the course;
- an increase to 135 the number of people involved in the EHR effort;
- spin-off of a new UCSC "course offering" in Education (Ed 286) based on CfAO workshops and short courses. Ed 286 is designed for science and engineering graduate

students, and the enrollment increased from 14 in 2003 to 20 in 2004. The UCSC chemistry department accepted this course as an elective course outside the department that can be counted towards the Ph.D. degree.

- an increased involvement of Maui Community College (MCC) with CfAO programs (2 faculty members assisted in courses); and
- a short course in optics for Akamai Maui interns that has become a pilot for a new instrumentation course for MCC. It has also contributed to increased community support, recruiting efforts for new students, and efforts to create better projects.

EHR programs have a significant impact on the educational development of the interns and graduate students. A majority of the 11 graduate students from three CfAO sites interviewed by the Site Visit Committee mentioned that the PDW was as major factor in their graduate experience and, as a result, in their future career plans. Graduate students at Rochester used their experiences from the PDW to develop inquiry-based learning demonstrations for Saturday open-house programs for underrepresented minority students from the Rochester community.

The 2004 Site Visit Committee stated “The Education and Outreach (EHR) Theme continued making significant progress and is a model for NSF Science and Technology Centers and other organizations and institutions. Their programs are outstanding meeting or surpassing all expectations.”

The following year the Center increased the linkages between CfAO and organizations that served significant numbers of underrepresented groups. Eighty-six percent of the 43 interns that participated in the mainland internship program, remained enrolled in a Science, Technology, Engineering and Mathematics (STEM) programs of study or had entered the STEM workforce. Six interns entered STEM graduate study in 2005 (4 of these were from underrepresented groups). The Hartnell Astronomy Short Course continued to be a successful recruiting tool and that college awarded CfAO the Hartnell President’s Partnership Award for Excellence in 2005. The committee commended the CfAO for its accomplishments in increasing the participation of underrepresented minorities.

The 2005 Site Visit Committee especially commended CfAO’s outstanding efforts within the Maui community. “Their collaboration with the Maui Community College resulted in the development of a new astronomy course. Additionally, their partnership with the Maui Economic Development Board, the Maui Community College, and the Air Force Maui Optical and Supercomputing Site (AMOS) stimulated new research collaboration and could well serve as a model for other islands.”

A continuing challenge faced by the CfAO EHR has been the development and implementation of projects on the Big Island of Hawaii. Mauna Kea is extremely important to the astronomical community, but weak local community support and involvement are areas of concern.

The Committee encouraged CfAO to continue working with their colleagues on Maui and the Big Island to build support for the implementation of an engineering technology degree program. Given the large number of underrepresented students that attend community colleges, this degree program would have the potential for significantly increasing the diversity of STEM disciplines and would be an investment in the future economic health of Hawaii.

The CfAO education program had an impressive number of meetings and workshops during Year 6. These included the Big Island Education Meeting, the Forum for Observatory and Technical Education, an NSF presentation (Opening Doors in Hawaii) and various meetings with observatory

directors and other personnel. Additionally, CfAO sponsored the UH Hilo Internship Forum and continued the annual Hartnell Astronomy Short Course.

CfAO's efforts to integrate research and education were especially commended. In particular, the Committee mentioned the sponsorship of the Education 286 course, a spin-off of the Professional Development Workshop. This course is taught at the graduate level and is especially designed for scientists and engineers who want to explore science inquiry teaching and learning. The Year 6 site visit Committee urged the Center to continue working with the University of California, Santa Cruz (UCSC) Department of Education to refine and expand this course.

The 2005 Site Visit Committee commended the CfAO management on their efforts to make EHR an integral part of CfAO rather than an add-on. "This integration greatly facilitates the Center's effort to effect a smooth transition to the post-NSF funding era. Many of the projects that have been initiated through the Center funding are likely to continue to be maintained through funding to support internships and graduate students." The Committee strongly recommended that teaching programs be institutionalized within the UC and Hawaii educational systems and hoped that the Associate Director for Theme 1 would remain actively involved to assure a successful transition. The Committee hoped that the opportunities for obtaining funding for education to develop a new center in Hawaii that will involve the major observatories, community colleges, and high-tech industries will be pursued.

The 2006 Site Visit committee summarized their assessment of the Theme 1 activities as follows: "The theme continues to show excellent progress in its current activities and has begun to develop significant, well thought out, and realistic plans to move the CfAO Education and Outreach efforts beyond the end of NSF funding. The plans to institutionalize the Professional Development Program by means of the Institute for Science and Engineering Educators, and efforts associated with the proposed Maui Workforce Initiative should provide a solid foundation for future Theme 1 efforts. To help sustain CfAO-related core efforts beyond Year 10, the committee feels that the hiring of a development officer must be a high priority."

Theme 2 – Adaptive Optics for Extremely Large Telescopes (ELTs)

In 2003 the NSF Site Visitors commented favorably on the decision to define a goal with clear objectives in multi-conjugate adaptive optics (MCAO) for ELTs and to focus on advanced concepts for sodium laser guide stars and modeling and simulation codes. The visitors recommended continuing development on the fiber based guide-star lasers at Lawrence Livermore National Laboratory - "these high risk, high payoff lasers may provide a robust and lightweight alternative to the currently used dye lasers.

Laboratory for Adaptive Optics (Moore Foundation Funds)

NSF CfAO funds were insufficient to develop and support a new AO laboratory while concurrently maintaining its research programs. Consequently the University of California at Santa Cruz made a formal proposal to the Moore Foundation to fund a Laboratory for Adaptive Optics (LAO) and was subsequently awarded a grant of \$9.6 million. The funds were to be used for the refurbishment of existing laboratory space and to support researchers in the first three years of the laboratory's operation. To ensure continuation of laboratory funding beyond the life of the CfAO, the LAO is officially a unit of the Lick Observatories with a close affiliation to CfAO programs in astronomy.

The plan to develop a test bed to anchor simulation models using the recently awarded Moore Foundation funds was seen by the Site Visit committee as an opportunity to “significantly enhance the Center’s ability to contribute to the ELT community.”

The Year 4 visit by the NSF was part of the CfAO funding renewal process. The Committee unexpectedly expressed several concerns about past performance and lack of tangible deliverables for Adaptive Optics for Extremely Large Telescopes (Theme 2), and the uncertain prospects for the external funding of Extreme Adaptive Optics (Theme 3) goals. There was also comment on a perceived lack of knowledge transfer from these themes: “Dissemination of experimental data and convening of technical hands-on workshops for laser guide star science and techniques should be key components in knowledge transfer activities.”

The CfAO response noted the need to convey “to the broader AO Astronomy community the considerable progress it has made in identifying national goals for the application of Adaptive Optics, the strategy and infrastructure (including the Laboratory for Adaptive Optics) that it is assembling to meet these goals, and the specific new results obtained using the Lick Observatory laser guide star facility. These two themes are difficult to concisely describe, as the identified goals in both cases are long term and costly to achieve. The ambitious goals of Themes 2 and 3 were identified during the CfAO’s Strategic Planning process in Year 2, and were approved by the External Advisory Board, Program Advisory Committee, and Site Visit Committees. The research underway in Theme 2 varies from specific tasks such as laser development to more clearly delineating broader issues and exploring potential solutions, for example, in new architectures for adaptive optics on Extremely Large Telescopes. In all cases, however, it was agreed that publication of results and their presentation at professional meetings was an extremely important component of dissemination that the CfAO must continue to emphasize.”

For both Themes 2 and 3, the CfAO had itself concluded that NSF funds alone were not sufficient to carry the programs through to completion. “This was recognized at the onset and we are actively seeking funds from other sources to complete these ambitious hardware projects. Considerable thought has been applied to this issue, and funding strategies (with decision trees) have been identified. However, as discussed in the Renewal Report for Theme 2, Years 6 to 10 budgets and plans are not predicated on additional funding from any other source. They are based on understanding the fundamental concepts underlying the future development of Extremely Large Telescope systems. As discussed, any additional funds would be applied to the development of expensive full scale prototypes and hardware that are not included in the current plan.”

The funding issues raised in the Year 4 Site Visit were mostly put to rest the following year in which the CfAO reported “The ELT landscape in the U.S. has changed dramatically. The Caltech CELT project, the AURA GSMT project, and the Canadian VLOT merged into a new Thirty Meter Telescope (TMT) project. The TMT now has sufficient funding to begin design work. A Project Manager was hired, a Project office established, and various committees organized. The CfAO director, Jerry Nelson, was appointed the TMT Project Scientist. It is of note that the TMT AO working group is largely composed of CfAO members, who continue to actively investigate the feasibility of various AO concepts in consultation with the SAC and others.”

The Year 5 Site Visit Committee recommended that “the CfAO focus on areas of ELT technology and software development that have broad applicability, independent of any particular ELT concept or design; these areas will form the CfAO legacy that will endure when and if an ELT is constructed - there being no guarantee that a final ELT design would resemble current conceptual designs.”

The Committee noted that “there was no discussion of interactions between the CfAO and the ongoing Gemini MCAO project in the Year 6 Annual Report. The work done at CfAO on MCAO algorithms and optimization has now moved to the stage of prototyping and verification. Going beyond the laboratory MCAO prototype, LAO is now designing the on-sky experiment ViLLaGEs, where several key technologies will be tested, namely the fiber laser, uplink compensation, MEMS and open loop compensation. The Committee strongly supports this activity....The Committee views the LAO as a key element ensuring the transition of CfAO to the post NSF funding era..... The LAO is a unique resource for preparing specialists with hands-on experience in AO. Such specialists are in strong demand.”

The Committee also commented favorably on several other CfAO activities including

- the designing of a Next Generation AO (NGAO) system for the Keck Observatory. This would offer useful AO compensation at visible wavelengths.
- The developing and testing of special radial-format CCD detectors, designed to overcome spot elongation, one of the major problems of LGS AO on ELTs. The committee noted that the University of Arizona has another approach to remove spot elongation, namely dynamic refocusing which is being tested on-sky.

Finally the Committee recommended increased collaboration between CfAO and astronomers in both the national and international communities as a successful transition to the post NSF era.

Progress on Laser Guide Stars

In 2006, the Center reported “that the Chicago Sum-Frequency Laser had been shipped to Palomar Observatory for testing with the PALAO adaptive optics system. It produced 3.5 W for a period of 60 hours in the lab and remains to be tested on the telescope.” The Committee congratulated the CfAO staff on this impressive turnaround and commended the management and the Blue Ribbon Committee¹ on their analysis of the underlying problems with the laser and instituting a plan to accomplish the turnaround.

Progress had also been made with the LLNL fiber laser by scaling the 589 μm power level to 0.8 W. Hardware problems with the Neodymium fiber laser master oscillator had led to a six-month delay in laser testing while it was being repaired in Europe. Concern was expressed with the slow pace of progress for this laser and the loss of LLNL internal funds that helped sponsor this development.

A recommendation was made that the CfAO define general guide star laser performance requirements for the astronomical AO community in order to guide them in the selection and development of the laser technology best suited for deployment at various telescopes.

In Year 6 the NSF Site Visit team’s report summary stated “The Center has already set up the LAO for modeling multi-conjugate adaptive optics and has made major progress on simulation tools towards adaptive optics for extremely large telescopes (ELT).”

With reference to Theme 2, the report contained the following statement “The highest priority of the last US Decadal Survey for ground-based night time astronomy is the design and development of a thirty-meter class extremely large telescope (ELT) using adaptive optics to achieve diffraction-limited resolution at infrared wavelengths. Currently there are two parallel initiatives working towards this goal: The Thirty Meter Telescope (TMT, 30-meters in aperture) and the Giant

¹ Panel of experts assembled by CfAO to act as consultants and resolve difficulties being experienced.

Magellan Telescope (GMT, 22-meters in collecting aperture) consortium. CfAO addresses the needs of both programs even though, because of its home within UCSC, it is more focused on the TMT design and development.”

Other ELT concepts under development at this time, with Adaptive Optics as an essential component, included the 100-m OWL and 50-m Euro50 concepts being pursued in Europe.”

The Year 6 Site Visit committee identified the technological challenges that must be met for Adaptive Optics to be successfully employed in ELTs. These include the development of:

- (a) Powerful (>50W) sodium-wavelength (Na) lasers, preferably pulsed to enable mitigation of the so-called perspective elongation resulting from the thickness of the Na mesospheric layer and/or to enable the mitigation of Raleigh and Mie scattering in the lower atmosphere;
- (b) Wavefront sensors for many sub-apertures of ELTs;
- (c) Wavefront sensors with accurate response over the full range of atmospheric wavefront distortions;
- (d) Adaptive secondary mirrors to minimize the telescope emissivity and maximize its throughput;
- (e) Smaller adaptive mirrors when multi-conjugate adaptive optics (MCAO) or its variants multi-object adaptive optics (MOAO), *etc.* are used.
- (f) Algorithms to design, build and execute MCAO *etc.*;
- (g) Methods of using the short laser pulses to mitigate the effects of perspective elongation in wavefront sensors;
- (h) The extension of AO to visible wavelengths; and,
- (i) The possible use of LGSs on ELTs in daytime for thermal infrared observations where the daytime sky brightness is acceptable.

The CfAO is actively engaged in items (a), (b), (c), (e), (f), (g) and h.

In 2004 the CfAO had identified four goals for the ELT program. Progress on these main goals were reported in Year 6 as follows:

1. Develop at least one workable point design for wide-field adaptive optics on a 30-m telescope.

Several point designs have now been developed, in partnership with teams from the TMT programs. The MCAO test bed at the UCSC Laboratory for Adaptive Optics (LAO) was completed and this system has begun testing MCAO hardware components, atmospheric tomography software, and systems modeling needed for an MCAO for ELTs.

2. Develop partnerships to co-fund hardware technology development for key components, including lasers.

Laser development will be addressed in a following section. However another key technology that affects various ELT AO systems is deformable mirrors (DMs). The CfAO has currently focused on small, high-actuator-density micro-electromechanical systems (MEMS) mirrors rather than on larger adaptive mirrors that are better suited for wide-field MCAO applications. MEMS mirrors are ideally suited for both astronomical MOAO and AO applications in vision science. This synergy makes it particularly appropriate for CfAO to pursue the MEMS.

3. Develop techniques for doing quantitative astronomy with laser guide stars.

CfAO scientists continue to make valuable science observations with the Lick and Keck LGS AO systems. The Year 6 Site Visit Committee recommended that CfAO continue to develop point

spread function (PSF) reconstruction algorithms to generate the PSF for each observation (with or without laser guide stars). This has great potential to make all AO observations more efficient and increase the quality of the results of AO observations on any telescope. The Committee further commended the CfAO for their continuing efforts to make the results of the CfAO Treasury Survey (CATS) public, in both raw and reduced forms, as they become available.

4. Pursue astronomical science related to AO on 30-meter telescopes.

The science goals of CfAO astronomers in Themes 2 and 3 should take into consideration the emerging and evolving science cases for ELTs. The Committee was particularly impressed by the results obtained on the region surrounding the Galactic Center from observations made with the Keck telescope laser guide star system.

Site Visit Reports on Laser Guide Stars AO Astronomy)

In its 2005 Annual Report, the Center reported on its progress towards the development of Sodium guide star lasers and provided an overall perspective on the current state of guide star laser technology. The Center was cognizant of the key technical issues related to the use of guide star lasers such as spot elongation, Raleigh and Mie scattering (due to cirrus), the need to mitigate the cone effect, and to minimize fratricide in the scattering when using multiple guide stars. These issues could be addressed using pulsed guide star lasers and the Center was moving in this direction. Center encouraged activity included:

- Development of commercial mode-locked guide star lasers by Coherent Technologies Incorporated (CTI); and
- Development of pulsed fiber lasers at LLNL under funding from NSF's Adaptive Optics Development Program (AODP).

The Center's overall assessment was that these activities, along with the earlier US Air Force's development of a 50-W rod-based guide star laser, provide several reliable options for future guide star laser needs.

The Center's efforts on the Chicago Sum-Frequency Laser have focused on supporting the installation and integration of the laser with the Palomar Observatory adaptive optics system (PALAO). The Laser power had been scaled from 3.5 W achieved last year to 8 W, with the goal of projecting 4 W onto the sky. At the time the committee met the power projected into the sky with the 8 W laser had not been determined.

The 2005 Site Visit Committee recommended that CfAO document the Palomar laser design in a technical report. While this laser does not have the appropriate pulse format to address spot elongation, it is capable of addressing Raleigh and Mie scattering and the significance of this should be evaluated and documented. In addition, CfAO should begin documenting reliability-related issues as the laser accumulates more time at Palomar.

Progress had also been made with the LLNL fiber laser by scaling the yellow power level from its initial 0.8 W to 2.7 W, but still short of the goal of 5 – 10 W. The Neodymium fiber laser had been repaired and was now working at an acceptable level but problems were found with the erbium (Er) amplifier that had limited the available pump power at 1.58 μm to 6 W. In addition, damage problems with the Periodically Poled Potassium Titanyl Phosphate (PPKTP), sum-frequency crystal had necessitated shifting to a relatively newly developed crystal, periodically poled stoichiometric lithium tantalite (PSSLT). LLNL planned to perform experiments with a new Er fiber amplifier and PSSLT crystals in late September 2005 and that would conclude the continuous wave (CW) efforts.

The 2005 Site Visit Committee continued to be concerned with the slow pace of progress for this laser but recognized that in part, this was due to the loss of LLNL internal funds that had in the past helped sponsor this development. It hoped that a CW demonstration of 5 – 10 W would be performed as scheduled and documented as a technology benchmark for an efficient compact and highly reliable guide star laser before moving on to pulsed systems. The Committee was concerned that pulsed systems have their own set of performance risks and the availability of a 5 – 10 CW source could be a significant improvement over existing dye lasers and provide an interim solution on the path to more desirable pulsed lasers.

The Center staff was also involved with synergistic work on a pulsed fiber approach at LLNL that was funded by the NSF Adaptive Optics Development Program (AODP), and was closely following a commercial laser development at CTI. As the Center transitions to pulsed fiber sources, the Committee hoped that the AODP work would help to share risk and accelerate the development of next generation pulsed fiber guide star lasers.

The availability of a commercial mode-locked, amplitude modulated (pulsed) guide star laser source in 2005 was a significant benefit to the astronomical community. The delivery of a CW mode-locked 12 W laser to Gemini North and the commitment to deliver a 20 W laser to Keck and a 50W laser to Gemini South on a firm fixed price basis indicated that CTI was developing useful products and was ready to address the guide star laser market with the pulse format needed. There was concern that CTI's acquisition by Lockheed-Martin might make their future direction uncertain. Thus the Center should continue its vigilance in developing alternate sources and remain engaged with CTI for potential technology transfer should they be forced out of business.

The Site Visit Committee recommended that the CfAO define guide star laser performance requirements for the AO community in order to guide it in the selection and development of the laser technology best suited for deployment at various telescopes.

The 2006 Site Visit Committee expressed its concern at the slow rate of progress on the LLNL fiber laser but recognized that this is a relatively high risk development. The Committee hoped that a demonstration of > 5 Watts is achieved as scheduled and documented as a technology benchmark for an efficient, compact and highly reliable guide star laser.

The Chicago Sum frequency laser continued to operate on Mt. Palomar producing 8.5 W with 4 W projected on the sky. The team at PALAO succeeded in closing the loop on the AO system and looks forward to LGS/AO enhanced astronomical data in the near future. The Site Visit team commended CfAO and PALAO on the progress made.

Transition Plans

The 2006 Site Visit Committee commented that the CfAO is in an excellent position to lead the astronomy community's work on the MCAO point design for ELTs and also in its participation in the implementation of extreme adaptive optics via the GPI instrument for Gemini. Because of the CfAO's work on Atmospheric Tomography and MEMS technology, the CfAO should continue in the design of a MOAO instrument for 30-m telescopes where it appears to be in an excellent position to take the lead in the eventual construction of such an instrument.

Theme 3 – Extreme Adaptive Optics (ExAO)

In 2002, the NSF site visit team commended the CfAO for defining an aggressive program that included a plan to install an ExAO instrument at Gemini or Keck within the next five years and

the modeling and vigorous observing that has been performed to identify the role of ExAO in discovering and directly imaging new planets around other stars.

As was noted in Theme 2 above, the 2003 Site Visit report was critical of both Theme 2 and Theme 3 programs. Specifically they said that the funding of instruments for both Themes was beyond the scope of available NSF CfAO funds. Later developments in Theme 3 have put to rest these fears. In addition, the report indicated a level of disappointment at the lack of detail in the Theme 3 presentation to which the Center provided a written response. “We regret that a perception was created that there was reluctance to provide such detail. We had prepared our Theme 3 presentations under the (mistaken) assumption that the Committee would want to see the “big picture” without a great deal of technical detail. Some of our technical material within Theme 3 has been already published, and more will be published later this year. The perceived delay is not uncommon with the requirements of data acquisition, analysis and presentation. In any new area there are technical questions that need to be addressed, but we are confident that promulgation of our design both in the literature and at conferences will allay the concerns of the Committee.”

In 2004, considerable progress had been made in conceptual studies and the potential for funding an instrument at an observatory. The Site Visit committee endorsed the then current CfAO roadmap for Theme 3 and noted “CfAO continued to pursue the design and construction of an extreme AO system for direct detection of extrasolar planets and had assembled a broad multinational team to tackle this program. CfAO had also developed simulation tools to address complex science/instrument tradeoffs with both CfAO and the Laboratory for Adaptive Optics (LAO) providing important seed funding for fostering this effort. The CfAO led team had been selected as one of two teams in competition for an ExAO design for a Gemini Telescope. CfAO had also begun modeling efforts to identify the science reach of a high-contrast AO system on a 30-meter telescope.”

During Year 6 (2005), a major effort of CfAO and its partners was the preparation of the proposal for the Gemini Extreme AO Coronagraph (ExAOC) contract, which was subsequently accepted and fully funded by Gemini – the instrument name being changed to the Gemini Planet Imager (GPI). With LLNL the lead institution, CfAO would continue its research activities associated with high-contrast AO instruments. The Site Visit Committee considered this a very significant achievement by CfAO and offered congratulations on this great success. The role of CfAO in providing synergy among different groups involved in the ExAOC proposal and matching their areas of expertise had been crucial to the proposal. CfAO supported or developed several enabling technologies for this and future ExAO instruments, including:

- i) MEMS deformable mirrors;
- ii) Fast optimal wave-front control; and
- iii) Apodized-pupil coronagraphs.

The newly created LAO (an entity of the Lick Observatory) had been actively involved in the studies of high-contrast imaging techniques and the Committee was impressed by the laboratory test-bench experiment as a proof-of-concept for the apodized-pupil imager.

CfAO partners were actively involved in astronomical programs of high-contrast imaging, preparing to use ExAOC and other similar instruments as they become available. A strong international team was formed around the development of the ExAO science case. This work would continue through Years 7-10 and beyond.

The 2005 Site Visit Committee endorsed the CfAO work plan on Theme 3 for Years 7-10. “The effort will be primarily directed to research and development (R&D) and science support of ExAO, without duplicating or substituting the work on actual construction of the Gemini instrument. The combination of CfAO and LAO positioned them to take the lead in future projects of ExAO instruments and the visiting committee strongly encouraged CfAO to compete in future projects related to ExAO, capitalizing on its achievements.”

The 2005 Site Visit Committee recommended that CfAO extend its role “in the coordination of ExAO research by engaging new partners in these activities – for example, by organizing thematic workshops or conferences and keeping the community informed on the CfAO website.”

The 2006 Site Visit team stated “the successful proposal to Gemini to build GPI (ExAOC) was an outstanding demonstration of how CfAO can bring together various groups in a successful collaboration and support the enabling technologies of their programs.” The committee understood the basis for CfAO funds supporting the underlying research for GPI while the hardware development was funded by the Gemini program. However noting that the technology and hardware requirements were an ambitious undertaking within the proposed development time frame, they suggested that if needed, consideration be given to divert CfAO funding to certain aspects of the hardware development to ensure the project met its time deadline. The Site Visit team reiterated advice from the previous year that the GPI team engage the wider astronomy community in the progress being made on the GPI.

Theme 4 – Vision Science

In 2002 the Site Visit Committee commended progress in Theme 4: “The researchers in the vision science theme have continued to produce interesting scientific results and develop exciting new instruments for measuring the optics of the eye and viewing the retina in vivo. Particularly striking are the measurements using AO that show widely varying red/green cone ratios in persons with normal color vision. They have also demonstrated the ability of the confocal AO scanning laser ophthalmoscope to view different layers of the retina and to image individual red blood cells in retinal capillaries. Even more promising in terms of resolution, is the coherence-gated AO retina camera which is in the early development stage.”

In 2003 the visiting committee observed that “the instruments created in the theme are already beginning to find useful applications in clinical environments in imaging vascular disease at high resolution, monitoring retinal blood flow without fluorescein angiography, and tracking photoreceptor loss in retinal degenerative diseases. Future applications include tracking ganglion cell loss in glaucoma, and use in retinal surgery with an AO surgical microscope.

The Science in the Astronomy programs, the focus on instrumentation in the Vision Science theme and the increased interaction between astronomers and vision scientists also received positive comments. There was a major concern and some lesser criticism that are commented on below.

Theme 4 continued making advances in the application of AO to vision science instruments and in 2005 the Site Visit Committee observed that

- “1) The AO spectral domain OCT retinal imaging system at the University of Indiana became operational and created retinal images with the highest lateral resolution obtained to date, which, for the first time, allows visualization of the cone photoreceptor cells in a cross-

- sectional view. The instrument uses a spectral-domain OCT approach with AO correction of the wavefront in the detector optical train.
- 2) Detailed studies of eye motion were obtained from the AO scanning laser ophthalmoscope (SLO) at the University of California at Berkeley (UCB). This method was shown to be superior to the best eye tracking method currently in use (dual Purkinje image tracking).
 - 3) The position of the fixation point with respect to the center of the macula was measured at the University of Rochester (UR) with an AO ophthalmoscope.
 - 4) The fixation of the eye in the presence of normal eye movement was studied using the AO SLO at UCB. The fixation target was projected directly onto the retina by modulating the projected beam, so that the exact retinal area used by the viewer for fixation could be monitored continuously. This method has potential application in identifying and determining the viability of areas of functioning retinal tissue in diseased retinas.
 - 5) The AO retinal imaging system was used at the University of Rochester to visualize the cone photoreceptor mosaic and detect genetic photo pigment mutations.
 - 6) Measurements were made with the flood illuminated AO retinal imaging system to study variations in the cone reflectance over time periods of seconds. A model involving the assumption of changes in the index of refraction of the cones due to bleaching effects was used, with some success, to explain the phenomenon.
 - 7) Boston Micromachines Corporation (BMC) MEMS deformable mirrors were installed and operated successfully in AO retinal imaging instruments at UCB and UR. The LLNL AO phoropter was also retrofitted with a new BMC MEMS deformable mirror to take advantage of its increased stroke.
 - 8) Dye-marked retinal ganglion cells were imaged in experimental animals at UR.
 - 9) The members of the CfAO Theme 4 group obtained two Bioengineering Research Partnerships (BRP) National Institutes of Health (NIH) grants. The funds involved in these grants amount to \$15,000,000 over a 5-year period.
 - 10) Members of the Theme 4 group at UR have written a handbook on the practical aspects of employing AO in vision science. The book will be published by J. Wiley and Sons and is titled Adaptive Optics for Vision Science – Principles, Practices, Design and Applications.
 - 11) The Theme 4 group continued to effectively collaborate with other members of CfAO Themes on vision science issues.”

The NSF Site Visit Committee was highly impressed with these outstanding accomplishments.

In 2006 CfAO transferred the Adaptive Optics phoropter to Bausch & Lomb for evaluation to determine its commercial potential. Also in accord with the 2005 NSF Site Visit team recommendation, a limited number of retinal specialists in the Rochester and the Los Angeles areas were contacted to explore the needs for AO enhanced retinal imaging and the clinical viability of the AO phoropter technology.

Many of the goals for the final period of the NSF grant for the Theme 4 group have already been or are well on their way to being accomplished. The Theme 4 group is actively considering seeking support for establishing a new center that maybe called the *Center for Functional Imaging of the Retina*. While the use of adaptive optics would be one important and integral part of its activities, the Center's focus would be on the broader insights that can be obtained in studying the retina and vision with the new instruments developed and under development.

The 2006 NSF Site Visit Team added its commendation of the vision science instruments that had been developed and the resulting scientific research that was made possible both in animal and human subjects. The committee was particularly impressed by the fact that “the University of Rochester (UR) and the University of Houston patents had been licensed to Optos Ltd. for

incorporating AO in their existing wide field fundus camera. The imaging system will be marketed to optometrists for mainly screening purposes.....Additionally there are plans to develop “high-end” customized AO imaging systems by a future company that will involve researchers at UR who have contributed to the development of the current prototype instruments. Members of the Vision Science theme are also submitting two BRP renewal grants to the NIH. All of which is very promising for the future of this theme after the conclusion of NSF funding. The Committee stated that it is “highly impressed with the various efforts of Theme 4 in making available their findings and experience in AO imaging to the vision science community and being active in exploring other avenues for continuing AO retinal imaging research.”

MEMS Technology

The CfAO recognized very early that that advances in the functionality of MEMS deformable mirrors would result in their providing a critical enabling technology for three of the CfAO themes. Under its leadership funding has been provided for the development of MEMS deformable mirror arrays by several partner institutions, some without CfAO support. Several different technologies with differing levels of risk and potential performance capability have been supported. While the near term lower risk approaches meet the needs of the vision community, the ELT and ExAO applications for deformable mirrors require the higher risk, longer-term developments. There has also been an inherent risk in pursuing these goals in that the companies involved are relatively small and some did not survive the aftermath of the down turn in the telecom industry.

However in 2004 CfAO underscored its and UC Santa Cruz’s commitment to this important area of technology with the recruitment of a new faculty member who specialized in MEMS development, while continuing to fund MEMS deformable mirror development at Boston Micromachines Corp. and IRIS AO.

As stated earlier, MEMS Deformable Mirror Chips (DMCs) play a key role in the success of the three CfAO projects or Themes:

- 1) Theme 2, AO for Extremely Large Telescopes;
- 2) Theme 3, Extreme Adaptive Optics; and
- 3) Theme 4, AO for Vision Science.

Each Theme requires a different specification for the MEMS Deformable Mirror Chip – for example, mirror array count. In 2005 the CfAO team produced detailed specifications for each Theme to provide the broad MEMS industrial and university communities with guidelines for DMC development. More than five organizations were developing DMCs to meet these specifications. By circulating the new DMC specifications, CfAO hoped to stimulate additional interest in the MEMS community to address the challenge to design and manufacture large count (10,000 elements), large stroke (>10 μm) mirror arrays with supporting electronics.

In 2005, CfAO made substantial progress in the purchase and characterization of a 32x32 (1024 mirrors) DMC manufactured by Boston Micromachines Corporation (BMC). The evaluation of the BMC mirror chips highlighted the improved performance and utility of the DMC. The price for the 32x32 DMC was \$25,000 and that of the larger arrays under development substantially more. While the DMC price is less of an issue for telescope projects (Themes 2 and 3) it does impact the higher volume market projected for Theme 4 (Vision Science) where the price must be reduced to (at most) \$1000 - \$3000 per chip (albeit with fewer actuators).

The higher mirror count (4,000 – 10,000 elements) DMCs required for the telescopes are still in the development stage with a 1000 element DMC delivered in 2006 and 10,000 element DMCs scheduled for delivery in 2007. Of the MEMS development efforts funded by CfAO in 2005, the following progress was made:

- a) Boston Micro Machines (BMC) delivered and members of CfAO characterized a 140 element, continuous membrane DMC with a $\sim 4 \mu\text{m}$ stroke or mirror displacement, and a 4.4 mm aperture;
- b) IRIS AO made incremental progress with their hexagonal discrete planar element design.
- c) MEMX demonstrated their discrete, hexagonal planar element design with $50 \mu\text{m}$ stroke and greatly improved element flatness. This was excellent progress, but the company has not developed drive electronics for their device and went into liquidation in 2006.

In late 2005, BMC appeared to be the company most likely to deliver the first 4000 element DMC with at least a $4 \mu\text{m}$ stroke. The long-term goal for mirror stroke for Themes 2, 3 and 4 is at least $10 \mu\text{m}$, and a number of MEMS groups are attempting to meet this very difficult specification in 2006 – 2007.

Another challenge involves the architecture for the high voltage (~ 150 Volts) mirror driver electronics. The present electronics for the 1000 mirror array are off-chip electronics on pc boards. These will be used to drive the 4000 element DMC, but an on-chip or attached Application Specific Integrated Circuit (ASIC) architecture for electronics will be required for the 10,000 element array. Fully integrated on-chip electronics on the DMC requires a long lead-time design, fabrication and verification cycle and consequently a substantial increase in price. The 2005 Site Visit Committee commended CfAO for the substantial progress made in FY 2005 in the optical bench demonstration and characterization of a 32-x32 DMC and for the creation and circulation of detailed DMC specifications for Themes 2, 3 and 4.

The 2006 NSF site visit team commended CfAO for the fact “That there continues to be good progress in the design, fabrication and characterization of the Mirror Arrays required for the CfAO Themes.”

Knowledge Transfer

Over the years the CfAO has consolidated its Knowledge Transfer activities. Some highlights are:

- The Professional Development Workshops;
- The CATS program to provide raw and reduced AO data to the extragalactic astronomy community;
- Publication of the first significant papers based on the use of laser guide stars;
- Active commercial partnerships for MEMS development;
- The annual Adaptive Optics Summer School;
- The publication in June 2006 by Wiley of the manual “Adaptive Optics for Vision Science”;
- Continued networking between vision scientists and astronomers at all levels – Principal Investigators, post docs and graduate students.

The 2005 NSF Site Visit team report stated: “The transfer of AO knowledge by the CfAO to the broader community continued at an excellent pace,” and listed the range of Center activities over which this had occurred. The 2006 Site Visit report further commended the CfAO on its broad range of knowledge transfer activities, concluding with the statement “... the CfAO has been

instrumental in effecting an exciting transition from “AO development” to “AO deployment” for the nation’s vision science and astronomy communities”.

Center Management, Planning Process and Implementation of Plans for the Coming Years

The extensive NSF Office of the Inspector General audits of the CfAO have indicated sound financial and administrative management.

This view was reinforced by the Year 5 NSF Site Visit report that concurred with the External Advisory Board that the Center is working as a cohesive whole and the current management structure is effective. Astronomy expertise in signal processing is now being used in the Vision Science theme, both Astronomy and Vision Science benefit from work in MEMS development, and all themes benefit from EHR projects and vice versa. The review process for funding new and existing proposals is clearly defined, and runs well: vibrant proposal activity produces requests for 150% of available funds; 90% of projects are at least partially funded. Themes 1, 2, 3, and 4 have roadmaps and well-developed metrics for success.

The 2005 Site Visit report commended the Center for the smooth transition to a new Director (Claire Max replaced Jerry Nelson who accepted the position of Chief Scientist for the TMT program) and noted that Center management continues to be effective. They said that the Center continues to interact effectively with the UCSC Oversight Committee, External Advisory Board, and Program Advisory Committee. The current management structure has successfully brought together the AO community and integrated research and education. The Center held a special retreat to discuss transition strategy for continuing operations after NSF funding ends and solicited input from the members. Subsequent retreats and meetings continue to discuss aspects of the Center’s transition strategy.

The 2005 Site Visit Committee said that the management and transition strategy for Theme 1 is excellent:

- Following the CfAO strategic planning meeting (Half Moon Bay, August 2005), a small working group formed to explore institutionalizing the Professional Development Workshop by joining efforts with the UCSC Center for Informal Learning and Schools (CILS). The team met with UCSC administrators and made progress in developing the Institute for Scientist and Engineer Educators (ISEE). A proposal for UCSC funding was submitted in June 2007, requesting “bridge” funding to assist in developing ISEE.
- *Stars, Sight and Science* will be a fully institutionally supported program by UCSC in Year 10.
- *Akamai Maui Internship Program*: Proposals have been submitted to the NSF and the Air Force Office of Scientific Research (AFOSR) for \$3.2M over five years. This would help support the Maui internship program. The AFOSR has committed to \$125K/year for the 5 year period, if the NSF is willing to commit funds as well.
- *Hawaii Island Akamai Observatory Program* The participation of Mauna Kea observatories this year has significantly increased and it is hoped that this program will grow to be part of the community outreach by the observatories.

Currently in 2007, Theme 2 has successfully obtained independent funding to establish the LAO. The transition strategy incorporates competing for the design and construction of AO instruments

for the TMT or other telescopes. Design of visible light AO and laser guide star related research would also be pursued as possible areas to obtain funding. Identifying additional applications for the AO technology and obtaining independent funding to support the LAO are being sought during the transition period.

Similarly, Theme 3 has effectively utilized the Center's resources for the design of an ExAO system that resulted in a contract to develop such a system for the Gemini South telescope. The transition strategy involves implementation of this technology in other large telescopes and NASA planet imaging projects. The specifications of MEMS that are needed in astronomy and vision science applications have been thoroughly investigated. Theme 3 will continue interacting with companies and research groups that are developing MEMS.

Theme 4 has been successful in incorporating AO in retinal imaging systems and in obtaining research funding from BRP to build several AO retinal imaging instruments. A manual on the use of AO in vision science has been written and has been published. The transition strategy includes efforts for commercialization of AO retinal imaging instruments, evaluation of the clinical application of AO phoropter, continued progress for renewal of the BRP grants, and establishment of a new center for retinal functional imaging.

As a whole, the Center envisions continuing and strengthening its core functions at the end of the funding period from NSF. These functions include facilitating scientific interactions through regular workshops and retreats and providing education in optical science. Several non-NSF funding sources including endowment and the UC Office of the President have been identified as candidates for support of the Center's staff and core functions.

II - Research

II.1a CfAO Mission, Goals and Strategies

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

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

Strategies: CfAO will pursue its purpose and achieve its goal by:

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

II.1b Performance and Management indicators

Research – When preparing their proposals for funding, researchers must include progress milestones for the coming year. Subsequently on year's completion, when evaluating research results the Director and Executive Committee review the milestones predicted vs. results achieved and use this as a criterion for determining future funding. The quality of the research is taken into account based on results obtained, publications etc.

Administrative Management - The Center has a Managing Director (reporting to the Director) who is responsible for the day-to-day management and oversight of the various CfAO activities. These include budgets and expenditures, arrangement of retreats, workshops, and summer schools, report writing, facilities, etc. On completion, retreats and the summer school are reviewed and evaluated to determine if improvements can be made. The Center's External Advisory Board (EAB) meets with the Center Executive Committee each year and includes in their report an evaluation of management performance. The two recent NSF audits by the Office of the Inspector General (OIG) made a special mention of the high level of competence in the record keeping and administration of the Center.

II.1c Problems Encountered

Fiber Laser

The main technical challenge of the design is the 938 nm Nd: fiber laser, since the Nd³⁺ ions must operate on the resonance transition (i.e. 4F_{3/2}-4I_{9/2}), while suppressing ASE losses at the more conventional 1088 nm transition. A detailed study of the Nd³⁺ fiber laser system led to a

fiber design space in which it is possible to achieve significant gain at in the 900 nm band while maintaining a controllable level of gain in the 1088 nm band.

NSF Funding Delay

Year 8 NSF funding was delayed because of a computer database glitch within the NSF system. This led to funding not being received by CfAO till late in February 2007. A consequence of this four month delay was a late start for several projects. Milestones etc. had to be realigned in accordance with the later start date.

Rochester - Retinal Damage at Exposures Below Published 'Safe' Levels

Unexpected changes and even irreparable damage were observed in the RPE cell mosaic in response to the light levels that were used to generate autofluorescence images in monkey eyes at the University of Rochester. Surprisingly, these exposure levels were below the “safe limits” suggested by the American National Standard Institute. The observation of damage with ‘safe’ light exposures has important implications for all ophthalmic devices that employ short wavelengths for diagnostics or retinal imaging. In response, David Williams imposed a moratorium on AO imaging of human eyes until the nature of these changes were better understood. Because of the moratorium, some of the proposed milestones for Year 8 were not met and progress on other milestones was slowed. However, following a series of careful and controlled experiments on monkeys, the Rochester group is now developing new standards for the safe use of lasers. More importantly, they have established that the levels that had been used for human eyes (see year 7 report) were, in fact, safe. The light damage to the monkey was not a result of AO, nor was it a result of scanning a focused spot to form an image.

The following describes the nature of the damage observed. First, the intensity of the autofluorescence signal decreases after exposure to light. With low light levels the intensity of autofluorescence recovers and no long term changes are observed in the RPE cells. However, with more intense light exposures, the autofluorescence of the RPE cells appears permanently altered, indicating possible damage to the RPE cells. Figure II.1 shows results for a retinal location exposed to 150mW of 568nm light for 15 minutes. The pre-exposure autofluorescence image (Figure II.1b) shows the RPE cell mosaic at this location 2 degrees eccentricity from the fovea. The nuclei of the cells are dark and the light rings show the edges of the cells where lipofuscin has accumulated. The yellow square identifies the retinal area exposed. The immediately post-exposure autofluorescence image (Figure II.1c) shows a decrease of autofluorescence intensity at the light exposure site. However, no structural change in the RPE cells appears; each and every RPE cell is seen in the same location as the pre-exposure image. An hour and a half later, this decrease of autofluorescence intensity is still visible, although it has partially recovered with respect to the surrounding unexposed retinal area and again, no structural change of the cells is observed. Eleven days later, imaging this same retinal location shows dramatic changes have occurred at the photoreceptor and RPE cell levels. The reflectance image (Figure II.1e) appears cloudy over the light exposed area, and photoreceptors are not seen within this area but are visible in the unexposed surrounding areas. At the level of the RPE, the RPE cells are observed in the surrounding areas, but not within the light exposed area (Figure II.1f).

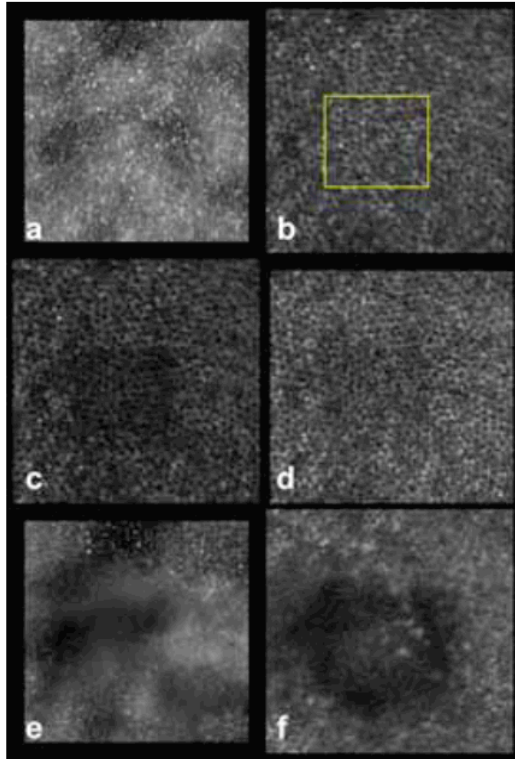


Figure II.1: Reflectance a) and autofluorescence b) image of approximately a 2 degree patch of the retina in monkey 903 before the light exposure. The yellow outline in b) shows the area of the retina exposed to 150mW of 568nm light for 15 minutes. c) Immediately post exposure image of the RPE layer. The intensity of the autofluorescence signal is decreased relative to the surrounding retinal area at the site of the light exposure. d) RPE image of the exposed area approximately 1.5 hours after the exposure. The dimming of the autofluorescence intensity has recovered slightly. Reflectance e) and autofluorescence f) images of the same area 11 days after the exposure. The reflectance image is dark in comparison with the pre-exposure reflectance image at the site of the exposure and the cone mosaic is not observed within the exposure. The RPE cells are not observed at the site of the exposure 11 days after the exposure. The surrounding areas do show RPE cells.

At another retinal location that was exposed to a lower flux, 110mW of 568nm light, for 15 minutes over a 2 degree field of view, immediate dimming of the autofluorescence at the site of the exposure was found, but no long-term structural changes were observed in the reflectance images or in the RPE autofluorescence images. The decrease of the autofluorescence intensity at the exposure site was quantified by examining the normalized ratio of autofluorescence intensity in the exposed relative to the unexposed areas. In 7 of 7 trials, an immediate decrease of the autofluorescence intensity was observed, the ratio between the pre- and post-exposure cases decreased by 17.5%. However, there was no significant difference in the ratio of autofluorescence intensity of exposed and unexposed areas 8 days later relative to the pre-exposure condition. Figure II.2 shows the decrease in autofluorescence intensity for exposures to 110mW of 568nm light for 15 minutes over a 2 degree field of view.

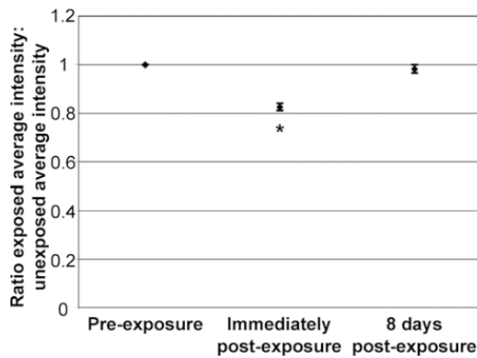


Figure II.2: Normalized ratio of exposed average autofluorescence intensity to unexposed average autofluorescence intensity. Data points show the mean \pm standard error from 7 exposures. On average, the ratio of autofluorescence intensity decreased significantly by 17.5% immediately post-exposure. The ratio of autofluorescence intensity from the same locations 8 days later show no significant difference from the ratios of autofluorescence measured pre-exposure.

There is no reason to believe that the temporary dimming of the autofluorescence signal represents retinal damage. Consequently, David Williams' group has concluded that the lower

exposure levels are safe for retinal imaging and have lifted their self-imposed imaging moratorium. The results are being prepared for publication and are being shared with members of the ANSI standards committee for safe use of lasers.

II.2a Themes

Theme 1 is the Education and Human Resources Theme and is presented in Section III

Theme 2: AO for Extremely Large Telescopes (ELTs)

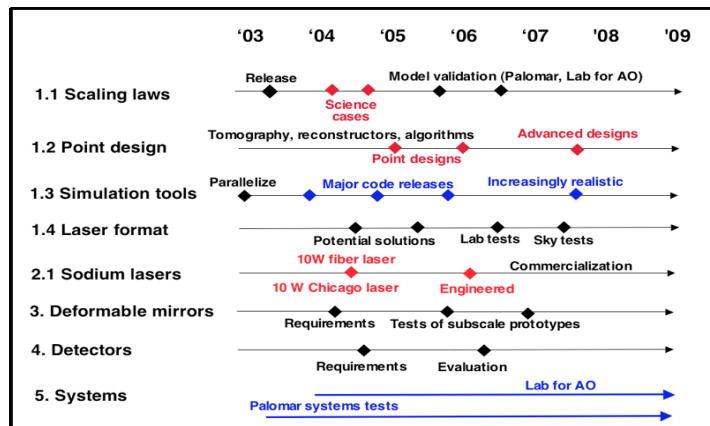
Introduction

In Year 8 we continued to pursue the development of adaptive optics for large astronomical telescopes including research in new system design, technology for lasers and deformable mirrors, and quantitative AO data analysis. Our activities included a healthy program of ongoing observational astronomy using adaptive optics systems on today’s largest telescopes.

The highest recommendation of the National Academy of Sciences’ Astronomy and Astrophysics Survey Report for ground-based astronomy² was the design and construction of a 30-m telescope equipped with adaptive optics. Developing an adaptive optics system for such a telescope is extremely challenging and requires an extension of almost every aspect of AO system design and component technology. The CfAO objective in this Theme for the second five years of the Center is to make a major contribution towards achieving this national priority, especially in areas where cross-institutional and multidisciplinary collaboration is required.

In Year 6, Theme 2 of CfAO was operating on a plan that stressed four development areas: 1) Develop at least one workable “point design” for multi-conjugate adaptive optics on a 30-m telescope; 2) Develop partnerships to co-fund long-range hardware technology development for key AO components, including laser guide stars; 3) Develop techniques for doing quantitative astronomy with laser guide stars; 4) Pursue astronomical science related to AO on 30-m telescopes, especially using laser guide stars, deconvolution methods, and spatially resolved spectroscopy.

In preparation for Year 7, we considerably modified the emphasis to focus now on three main areas: 1) MEMS deformable mirror development, 2) Sodium guidestar laser development, and 3) Astronomical science observing using AO. The readjustment reflects several developments during Year 6. A) the main theoretical results and concepts for a workable “point design” for an MCAO system (and new variants, such as Multi Object AO or MOAO) were mostly completed as



2.1 Theme 2 Gantt Diagram

of Year 6. In addition a number of large telescope projects have now received funding for design studies and are picking up the more detailed AO design efforts. Many of the participants in the CfAO funded analysis and modeling activity are now key players in these telescope design efforts. B) It has been recognized that in order for the CfAO to have an impact in AO component development, a goal by the end of Year 10 (the “sunset” year) should be to successfully demonstrate two key components: a MEMS deformable mirror and a pulsed guidestar laser. As a result, in Year 7, we directed our component development funding more strongly towards a few approaches, those which have shown the most progress and promise with CfAO funding so far. In a sense, this is a technology downselect with the goal now being to complete demonstrations of feasible technologies rather than to fund a wide variety of new approaches. The top level of the roadmap is shown in Figure 2.1.

MEMS Deformable Mirror Development

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

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

By Year 7, MEMS technology had advanced to the point where it was feasible to start the design and fabrication of a MEMS deformable mirror that could be used in general purpose adaptive optics systems for 30 meter class telescopes and for extreme adaptive optics on 8-10 meter class telescopes. The CfAO organized a consortium of users, partnering with the Thirty Meter Telescope (then a UC, Caltech, AURA, and CNRC partnership), the UCO/Lick Observatory, and the Gemini Observatory, to build a 4096 actuator MEMS over a two year time frame. This project successfully achieved the goals of the preliminary design phase (see Figure 2.2) and is now in the fabrication phase, with engineering grade test devices scheduled to come from the foundry at the end of this year, and a science grade device for the Gemini Planet Imager extreme adaptive optics system due to be delivered at the end of 2008.

Even as MEMS deformable mirrors are now becoming available on the commercial market, there is a continuing need to advance their capabilities both in stroke and scalability to larger numbers of actuators. The CfAO funded three research projects devoted to advancing MEMS technology during Year 8, two in Theme 2 and one in Theme 4 (Vision Science).

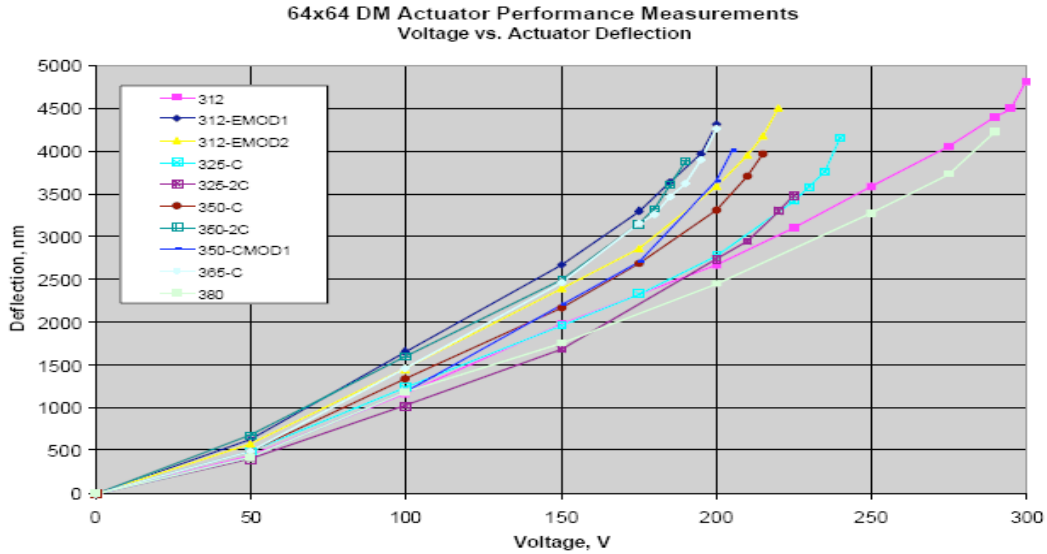


Figure 2.2. Test results of various designs of a prototype 4 micron stroke actuator for the 4096 MEMS which enabled selection of DM based on Actuator Performance (courtesy, Boston Micromachines Corporation).

Through-wafer Interconnects for MEMS DMs

Stephen Cornelissen of Boston Micromachines Corporation is leading this project to enable through-wafer electrical interconnects in silicon micromachined MEMS.

The fabrication of MEMS actuator arrays with through-wafer electrical interconnects is needed to meet the future needs of high actuator count MEMS based deformable mirrors for adaptive optics in extremely large telescopes, particularly to scale the number of actuators to more than 10,000 per device. Integration of the electrical interconnects with MEMS DMs eliminates the need for thousands of wirebonds and maintains a minimal optical footprint. The method combines existing through-wafer via technology with the proven fabrication processes developed for Boston Micromachines' deformable mirrors to provide an electrical signal path from the back of the device to the front of the silicon wafer on which the DMs are fabricated. The vias will electrically connect each actuator electrode on the device side of the wafer to a gold bonding pad on its rear. The interconnections will be electrically isolated from the substrate and each other by a thin, strong dielectric film coating within each individual via. They will be fabricated on the same spacing pitch as the actuator array and an actuator array will be fabricated over the through wafer interconnects. Subsequently functional and electrical testing of the device will evaluate the performance of this enabling technology.

The work will use commercially available fabrication processes from two different foundries. Silicon wafers, pre-processed to contain through-wafer interconnections at specified locations, will be used as the substrates for the actuator arrays. Successful completion of the proposed work will lead the way to economical high actuator count deformable mirrors with a minimal optical footprint, which in turn, will enable new instruments for astronomical adaptive optics.

The through-wafer interconnect fabrication process will be performed at IceMOS Technology, a commercial foundry specializing in supplying pre-processed silicon substrates for MEMS fabrication. By utilizing established, well characterized silicon manufacturing processes to fabricate the via-wafers, originally developed for the Analog Devices' I-MEMS program, the cost and overall risk to this development program is reduced. The via fabrication process used at this foundry is illustrated in Figure 2.3 and is compatible with the MEMS fabrication processes that follow. Although the via placement will be determined by the proposed device design, the via-fabrication process itself is considered mature.

These wafers will be used by MEMSCAP, a commercial MEMS foundry, as substrates for the subsequent processing used to produce heritage BMC MEMS actuators.

Progress to Date

This is a two-year project (Y8-9). Due to an unusual delay of the NSF funding in Y8, the project started later than planned. BMC began design work in March 07 and expect delivery of devices from the MEMS device fabrication run in late September, so while they have completed milestones 1 through 3 they are about 3 months behind the schedule, of their Y7 proposal shown below.

Three-Dimensional MEMS for Adaptive Optics

Joel Kubby of UC Santa Cruz is investigating the use of the 3-dimensional MEMS LIGA fabrication processes to prototype large stroke ($>10 \mu\text{m}$) actuators for use in adaptive optics systems. Y8 was the second year of this three year project.

The LIGA (Lithographie Galvanofornung Abformung / Lithographic Electroforming Molding) approach is a high-aspect ratio fabrication processes that creates metal (gold or nickel) micro-structures by bonding multiple, independently patterned layers (e.g. counter-electrode, actuator and face plate layers). The design freedom of this approach is being exploited to make single component high-stroke, high-order deformable MEMS mirrors with integrated face plates that can have large vertical heights of up to 1 mm. Since the sacrificial layer thickness can be up to $1,000 \mu\text{m}$, the design of high-stroke actuators is straightforward and does not require any new process development (e.g. deposition and patterning of thick sacrificial oxide layers as required in polysilicon surface micromachining approaches). This will enable simpler single-DM AO system designs where otherwise high stroke requirements would force the use of a second "woofer" DM. Since the electrochemical deposition process does not require high temperature fabrication steps, the deformable mirror arrays can be deposited on substrates with pre-fabricated through-wafer vias for addressing high-order (32×32 , 64×64 , 100×100) deformable mirror arrays. The actuators and face plate are made out of the same metallic materials so they are temperature matched and can be directly bonded. The materials used, gold actuators and face plates and ceramic substrates, are chemically inert making the deformable mirrors more robust to the open environment (i.e. not needing a hermetic-sealed window). Avoiding such optical windows is a large benefit for astronomical imaging applications where throughput and emissivity performance are at a premium.

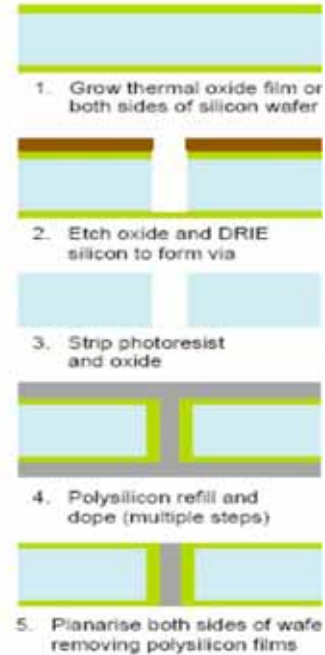


Figure 2.3. Illustration of through-wafer via fabrication process developed at IceMOS

The design concept is as follows: In order to form more complex structures from multiple electroplated layers, the layers can be diffusion bonded. A layer is formed on a sacrificial substrate and then bonded to a structural layer below. Once bonded, the sacrificial layer is removed to form a two layer device. The process can be repeated several times to form multi-layer structures. The proposed deformable mirror device requires three layers: a counter electrode layer, a spring layer that forms the top surface of electrostatic actuators, and a membrane face sheet mirror layer. Spacing between layers is 30 μm and 10 μm respectively. A schematic cross-section of this deformable mirror is shown in Figure 2.4.

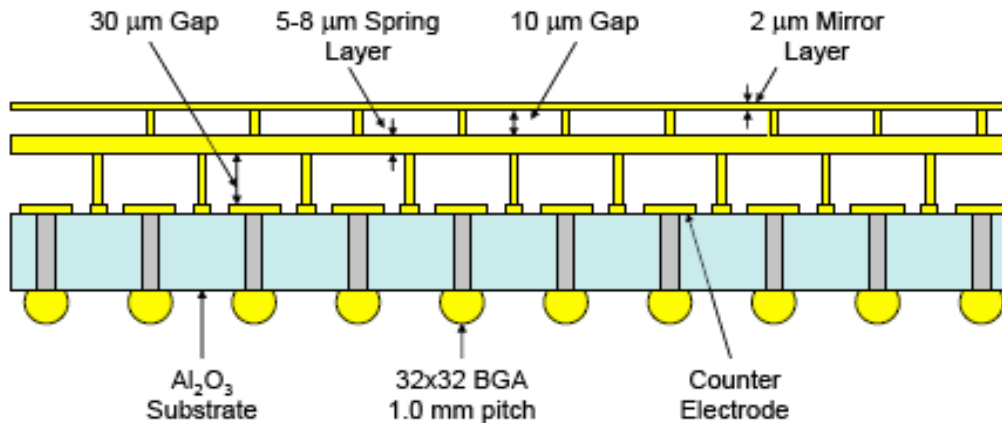


Figure 2.4. LIGA electrodeposition process multi-layer structure design for a MEMS deformable mirror.

The layers are formed from gold, which is highly reflective and chemically inert, enabling the mirror to be operated in an ambient environment without hermetic packaging, i.e. without a window in front of it. The alumina substrate will have through-wafer vias to allow scaling to large (10,000) array sizes without limitations due to routing wiring between actuators etc. Through-wafer vias will also allow bump bonding for hybrid integration of the actuator array with high voltage drive electronics.

In Year 8, samples of actuators and actuator arrays were fabricated on a glass substrate using the high aspect ratio processing, and then tested in the Laboratory for Adaptive Optics at UC Santa Cruz. Figure 2.5 (next page) shows microscope images of these devices. Actuator tests under a white light interferometer have demonstrated greater than 20 μ stroke, using <200 Volt potentials.

Year 8 Milestones:

- 16x16 array, fabrication run, started November 06
 - Phase one testing of actuators has been completed (see above).
 - Phase two face plate development activities have been delayed by 2 ½ months due to a delay in receiving the high CTE substrate materials that are required. Started in June 07, completion estimate August 07
 - Phase three integration of actuator array and face plate to start in September 07, completion in November 2007.
 - 32x32 array delayed to Year 9 due to vendor delay mentioned above. – Note: Given the delays, CfAO has recommended that in Year 9 Prof. Kubby perfect the

3-layer process (integrating through-wafer vias and facesheet bonding), before embarking on building a 32x32 device.

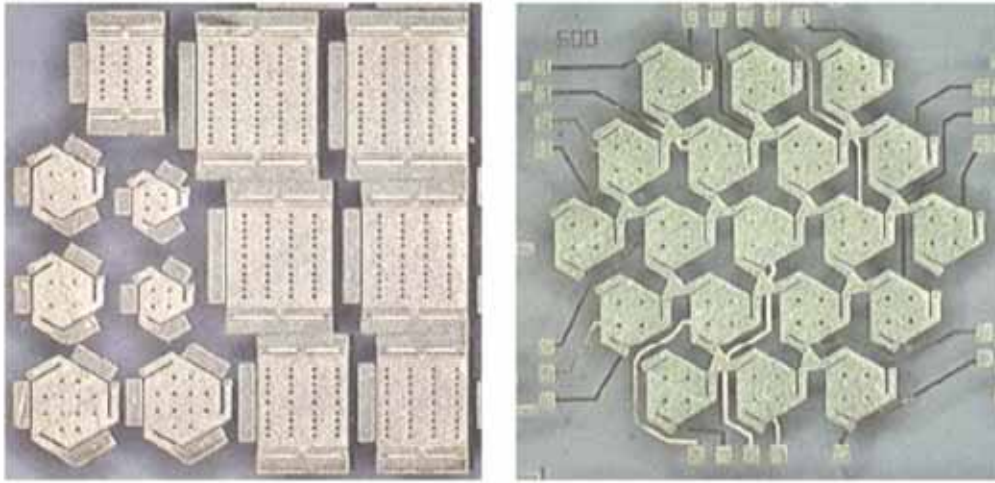


Figure 2.5. (Left) Hexagonal and rectangular actuators fabricated on a glass substrate using the high-aspect ratio electro-deposition process. (Right) An array of hexagonal actuators fabricated with the HT Micro electrodeposition process.

- Fabrication on substrates with through-wafer interconnects.
 - Delayed to Year 9 due to loss of supplier (Micro Substrates Corporation). Our MEMS foundry HT Micro believes they can provide substrates with through-wafer interconnects. These substrates will be used for the 32x32 arrays in year 9.
- Set up white light non-contact profilometry in lab.
 - Set-up in the Laboratory for Adaptive Optics. Completed April 07.

Sodium Guidestar Laser Development

CfAO funded two laser guidestar development efforts in Year 8: the CW fiber laser at Lawrence Livermore National Laboratory and the Q-switched laser at Palomar Observatory. Both lasers have achieved important milestones this year. However we are behind in our schedule to have these at 10 W and packaged for observatory operation by 2006. The LLNL laser has been reconfigured for pulsed operation (CW during a long macropulse) with the goals of this project realigned to be synergistic with the team's AODP funded activities. The new plan is to mount the laser at the Lick Observatory 40-inch telescope at the end of 2007 to coincide with a MEMS based AO experiment. The team has achieved 3.8 Watts in the lab at 20% duty cycle. The Palomar laser has projected 4 Watts on-sky and started astronomical observations with LGS AO this year. In Year 8 they have also taken steps to improve output power and diagnostics systems.

CfAO Sponsored Laser Guidestar Workshops

The CfAO sponsored two laser guidestars for astronomy workshops, which have had participation from major US and European observatories (Keck, Gemini, Lick, Palomar, European Southern Observatory), TMT and the US Air Force Starfire Optical Range. The purpose of these workshops was the interchange of valuable experience and data on the existing systems, as well as reports on progress in modeling proposed future systems for the next

generation of giant astronomical telescopes. We've learned that, in addition to the importance of spot-elongation and Rayleigh backscatter mitigating pulse formats, the exact spectral content of the laser (centered around the Sodium D2 line) is crucial to the efficiency of sodium fluorescent return. Workshop information and presentations are available on the web^{1,2} as well as a summary web page on all the astronomical AO sodium guidestar lasers currently in operation or under development.³

1 <http://lao.ucolick.org/twiki/bin/view/CfAO/LaserWorkshop>

2 <http://lao.ucolick.org/twiki/bin/view/CfAO/LaserWorkshop2007>

3 <http://lao.ucolick.org/twiki/bin/view/CfAO/SodiumLaserGuidestars>

LLNL Laser Development

LLNL is developing a versatile laser technology based on laser diode-pumped fiber lasers which are sum-frequency mixed in periodically poled materials to provide 589 nm light for LGS AO. The goal is to produce a 5-10 W fiber laser system at 589 nm. To date a lab prototype fiber laser has been demonstrated that functions at 2.7 W in continuous wave (CW) mode, suitable for a single LGS on a 3 - 10 m telescope, and at 3.8 W in a pulsed format for mitigation of spot elongation. The CfAO and AODP program baselines are now focused on a 10 W class pulsed laser as this best supports both the technical goals and the new priorities for Theme 2 established in Year 6.

Next generation laser systems must also be sufficiently reliable to enable routine operation in remote, somewhat hostile, observatory environments. Prototyping and experience are needed for low-cost, reliable, properly qualified laser systems, laser beam handling and launch.

The 589 nm laser system, shown in Fig. 2.6, is based on sum-frequency mixing an Er/Yb:doped fiber laser (EDFA) operating at 1583 nm with a 938 nm Nd:doped silica fiber laser (NDFA) in a periodically poled (PP) nonlinear crystal to generate 589 nm. Other solid state lasers currently under development generate 589 nm light by sum-frequency mixing Nd:YAG lasers operating at 1319 nm and 1064 nm. Since fiber lasers in the 1300 nm wavelength band are not presently available, the 1583 nm / 938 nm combination is being used. 1583 nm is a common telecommunications wavelength and so seed oscillators and fiber amplifiers are relatively easy to obtain commercially. The 938 nm laser is a more challenging one to amplify and the approach

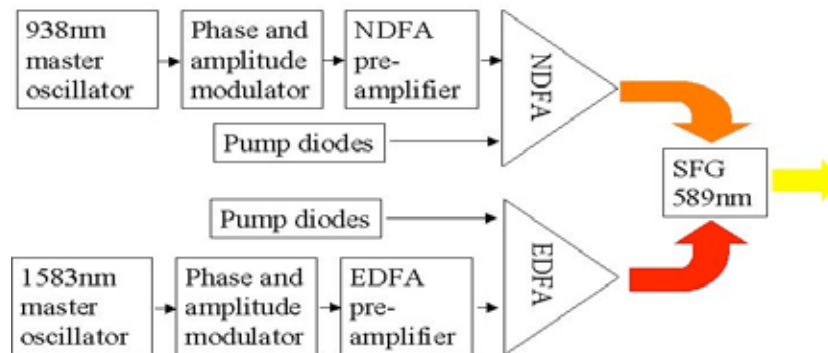


Figure 2.6: Block diagram of the 589 nm laser system. The laser mixes two high power infrared fiber laser outputs in a periodically poled material (sum frequency generator) to produce 589 nm light. Each of the infrared lasers uses cladding-pumped fiber amplifiers: a Nd:doped fiber amplifier (NDFA) for the 938 nm wavelength, and an Er:doped fiber amplifier (EDFA) for the 1583 nm wavelength.

being used is to cladding-pump a custom manufactured polarization maintaining fiber made by Nufern Corporation. Significant experience has been gained getting such a laser to operate efficiently while suppressing the parasitic 1088 nm line during the prior two years of this project. Periodically poled stoichiometric lithium tantalate (PPLST) sum frequency combining crystals were obtained from two sources, Professor Robert Byer's laboratory at Stanford University and a commercial source, Physical Sciences Incorporated. The 3.8 Watt 20% duty cycle laboratory result was achieved with the Stanford crystal.

An important feature of this design is the flexibility in setting the pulse format and the spectral content via the phase and amplitude modulators positioned after the seed lasers. With these, the pulse width can be adjusted as required for mitigating the sodium guidestar elongation on extremely large telescopes and also to tune the spectral content for maximal efficiency of return from the sodium layer.

From the commencement, an observatory field test has been planned, but we accelerated the effort this year. The fiber laser project is collaborating with the Visible Light Laser Guidestar AO Experiments (Villages) program at UCO/Lick Observatory, which is building a MEMS deformable mirror based AO system to be mounted on the Nickel 1-meter telescope at Mt. Hamilton. The objective of the first phase of Villages is to field and test a MEMS deformable mirror on-sky and the objective in the second phase is to field and test the fiber laser which will be projected through the telescope with uplink AO correction. First light for Villages Phase 1 is scheduled for the Fall of 2007 and first light of the laser is planned to take place in the summer of 2008. With on-sky testing of the laser, the sodium return per Watt as a function of the fiber laser's programmable pulse and spectral format will be able to be measured.

The main technical challenge of the design is the Nd: fiber laser, since the Nd³⁺ ions must operate on the resonance transition (i.e. $4F_{3/2}-4I_{9/2}$), while suppressing ASE losses at the more conventional 1088 nm transition. A detailed study of the Nd³⁺ fiber laser system led to a fiber design space in which it is possible to achieve significant gain at the 900 nm band while maintaining a controllable level of gain in the 1088 nm band. Optimization of the ratio of the fiber core and cladding areas permitted operation of the laser at room temperature by minimizing the gain at 1088 nm. Because this system is still in a non-field hardened research configuration, it has required significant tweaking to keep operating for experiments. In laboratory tests, 15 Watts at 20% duty cycle has been achieved with this laser. In Year 8 it was decided to field harden the system prior to performing additional 589 nm generation demonstrations and taking the system to the sky. This design was completed in September 06 and the components purchased. The amplifier fiber was delivered in May 07. Also the 938 nm seed laser was replaced with a packaged commercial oscillator from Toptica Photonics. The integration of the new 938 system is currently in progress.

Although the 1583 laser is, in principle, an available and mature technology, a number of problems were experienced with the amplifier, requiring return to the vendor (IPG Photonics) twice. The problem has since been remedied and this laser is now producing 14W at 20% duty cycle and is mounted in a field-hardened rack-mountable system.

The final key technology for the laser system is sum-frequency generation in a nonlinear crystal to generate 589 nm. Prior combined amplifier test results were performed with an uncoated Stanford crystal. This year, both the Stanford and the PSI crystals AR coated have been delivered and are now ready for integration into the sum-frequency stage later this year.

Palomar Laser Development

Professor Edward Kibblewhite from the University of Chicago has fielded and tested a sum frequency mode-locked laser at the Caltech Optical Observatory's Palomar telescope. In June 2006 the group propagated 4 Watts on the sky and closed the laser guide star adaptive optics control loop, obtaining a measurable improvement in the point spread function of a field star. The LGS AO system is now being used in "shared risk" mode science observing at Palomar.

Year 8 milestones included:

- Adding gain modules to increase the output power to 20 Watts – new heads have been installed and are currently being tested and commissioned at Palomar.
- Automating the frequency control and improving the beam diagnostics systems – Frequency and mode-locking control have been installed and are operational. Hardware for power, beam profile, and laser spectral diagnostics is installed, with integration to the control and real-time display system in progress.
- Replacement of the launch telescope primary (the spare optic used initially was discovered to have a crack in it!) – completed.
- Improvements to the beam tracking and transport system to assure a stable launch platform for the laser – in progress with help from Palomar staff.
-

A good portion of the above work is funded by Caltech and other funding sources. CfAO funding in Year 8 covered Professor Kibblewhite's activities at Palomar.



Figure 2.7. Chicago sum frequency sodium laser on sky the Mt. Palomar 5 meter Hale telescope, June 14, 2006.

Astronomical Science Observing Using AO

Theme 2 sponsors astronomical observing programs where the scientific conclusions are dependent upon the high resolution and contrast enabled by adaptive optics and laser guide stars. Three such programs in Year 8 were: the CfAO treasury survey, a large collaborative program for cataloging galaxies in the early Universe led by C. Max and D. Koo (UCSC); observations of planets, moons, and rings within our Solar System, led by I. de Pater (UCB); and tracking the motion of stars near the massive black hole at the center of our Galaxy, led by A. Ghez (UCLA).

CfAO Treasury Survey

CATS is a five-year survey using laser guide star adaptive optics to observe a large, deep sample of galaxies in the early Universe. The goal is to track the early assembly of galaxies like our own Milky Way, and to characterize the history of star formation in the Universe. Our near-infrared adaptive optics (AO) observations are up to 4 times sharper than those obtained by the Hubble Space Telescope. The scientific value of the data will be of importance to the broader astronomical community because the chosen sky fields all have complementary long-exposure observations at other wavelengths. These include space-based images from far infrared, optical to x-ray wavelengths, and ground-based images at radio and sub-mm wavelengths. We are making our AO data available to the public in an on-line archive. While observing galaxies in their youth, we are also probing super-massive black holes that are enshrouded by dust, galaxies magnified by gravitational lenses, and supernova explosions that can be used to measure the curvature and "dark energy" of the Universe. To date we have imaging data on 353 galaxies using natural guide star AO, and on about 100 additional galaxies in 10 laser guide star fields.

Project Objectives

CATS focuses on the largest Hubble Space Telescope (HST) fields designed for faint galaxy surveys. These include two GOODS (Great Observatories Origins Deep Survey) fields (N and S), the GEMS field (extension of GOODS-S), COSMOS (an equatorial field), and one of the four DEEP fields known as the Extended Groth Strip. These regions of the sky are being intensively studied by the most powerful ground and space telescopes, from radio to X-ray. CATS, with 8-10 m telescopes, is providing near-IR images and spectra at a spatial resolution (0.05 arcsec) 4 times finer than HST in the near-IR, and well matched to the optical diffraction limit of HST. The near-IR is particularly valuable because it penetrates dust-obscured regions, is sensitive to old stars, and, for high redshift objects, measures light in the rest-frame visible, allowing direct comparison to optical studies of local galaxies. The OSIRIS integral field spectrograph at Keck enables measurements of kinematics and spectra at high spatial resolution.

From fall '03 through spring '07, the CATS team was awarded 10.5 nights of Keck natural guide star AO time, 4.5 nights at Keck for non-AO spectroscopic follow-up, and 7.5 nights of Keck laser guide star time. We initiated a plan with Fred Chaffee, then Director of Keck Observatory, to obtain non-AO optical redshift data in the GOODS-North field in spring '03; these data were released to the astronomical community in 2004. The CATS team has published 10 papers to date with three more long drafts nearing submission. This year's papers include a high-z supernova and a gravitational lens observed with Keck LGS AO, as well as two very significant OSIRIS spectroscopy papers. CATS has successfully demonstrated faint object work in all the major extragalactic science areas that were identified in the original CfAO proposal: high-redshift galaxies and AGN, distant supernovae, and gravitational lenses.

CATS provides a superb Center-mode activity in several key ways: by unifying previously separate science programs providing an excellent platform for demonstrating the power of laser guide star AO; disseminating AO data and associated reduction and analysis tools; and focusing on the most intensely studied fields in the sky. CATS has become a catalyst for increasing the broad astronomy community's interest in laser guide star adaptive optics.

CATS Progress

This year the goal of demonstrating the capabilities of LGS AO in characterizing gravitationally lensed galaxies at high redshift was accomplished. CATS has developed an archive of AO data

and associated reduction and analysis tools, as a community resource. A third goal achieved was publication of a paper on a high redshift supernova observed with laser guide star AO.

The CATS project is divided amongst three separately led teams: UCSC (David Koo and Claire Max), UCLA (James Larkin), and Caltech (Matthew Britton). Progress of each is reported below:

UCSC

Due to the earthquake in Hawaii, our one night of OSIRIS time in fall 2006 was changed to imaging, which in turn was cancelled because of bad weather. Max's one LGS AO night in Dec 2006 provided 5 hours of useful LGS AO NIRC2 imaging, including an image of a gravitational lensed galaxy.

A major accomplishment for CATS has been the publication of a paper on the first LGS AO observations of a high redshift $z \sim 1.3$ supernovae (SN) observed in fall 2005. This SN paper is important in trying to achieve relatively high precision photometry, in showing off the advantages of AO in working with point sources atop of an underlying galaxy, and in demonstrating to the community that AO can provide unique data for distant extragalactic research. Melbourne has a working version of the database that can be viewed at:

//http://www.ucolick.org/~jmel/cats_database/cats_search.php

Username: cats Password: galaxy

The CATS team has collected Keck AO images of over 100 LGS distant galaxies and 353 NGS distant galaxies. In this initial data release, basic information on all of the CATS observations is provided. Reduced FITS images of the NGS observations are available for download. A data set in raw form is also provided for researchers to examine. An important part of the database is a library of NGS point-spread-functions (PSFs) to help constrain photometry. A second release is planned by this fall and will contain FITS images of the LGS data.

UCLA

The following is a list of the Year 8 goals and their present status:

1. Publish a paper on disk evolution based on the imaging survey, Summer 2007.
 - Survey paper covering all of the NGS fields is in final stages of preparation.
 - Matthew Barczys completed his thesis on the imaging survey and catalog.
2. Published two OSIRIS papers on candidate high redshift disk galaxy and on high-contrast imaging of a faint companion of GQ Lup
3. Publish faint companion, extragalactic merger history from NGS data, led by Matthew Barczys
4. Complete OSIRIS observations of more than 10 galaxies in the $z=1.25-1.75$ range. This is complimentary to the UCSC work at $z \sim 1.0$.
 - We've now detected 8 galaxies and have at least 1 more observing night during Year 8 to complete this milestone
5. Produce 2nd public data release of CATS imaging data, Spring 2007.
 - We anticipate the release of LGS data by the fall of 2007.

Caltech

In Year 8 the Caltech portion of the CATS project was entitled “Predicting the Keck LGS Adaptive Optics PSF for the CfAO Treasury Survey.” This project aims to use data from the TMT DIMM/MASS unit on Mauna Kea to demonstrate predictions of the PSF delivered by the Keck laser guide star adaptive optics system. The work is based on the successful demonstration of this technique (using natural guidestars) by Matthew Britton at Palomar Observatory. The work leading to its application to the CATS project has been delayed due to delays involving transfer of NSF funds to Caltech. However, preliminary analysis of CATS globular cluster images and acquisition of the DIMM/MASS profiles at Keck has been carried out and results look promising for applying the anisoplanatism model for PSF characterization.

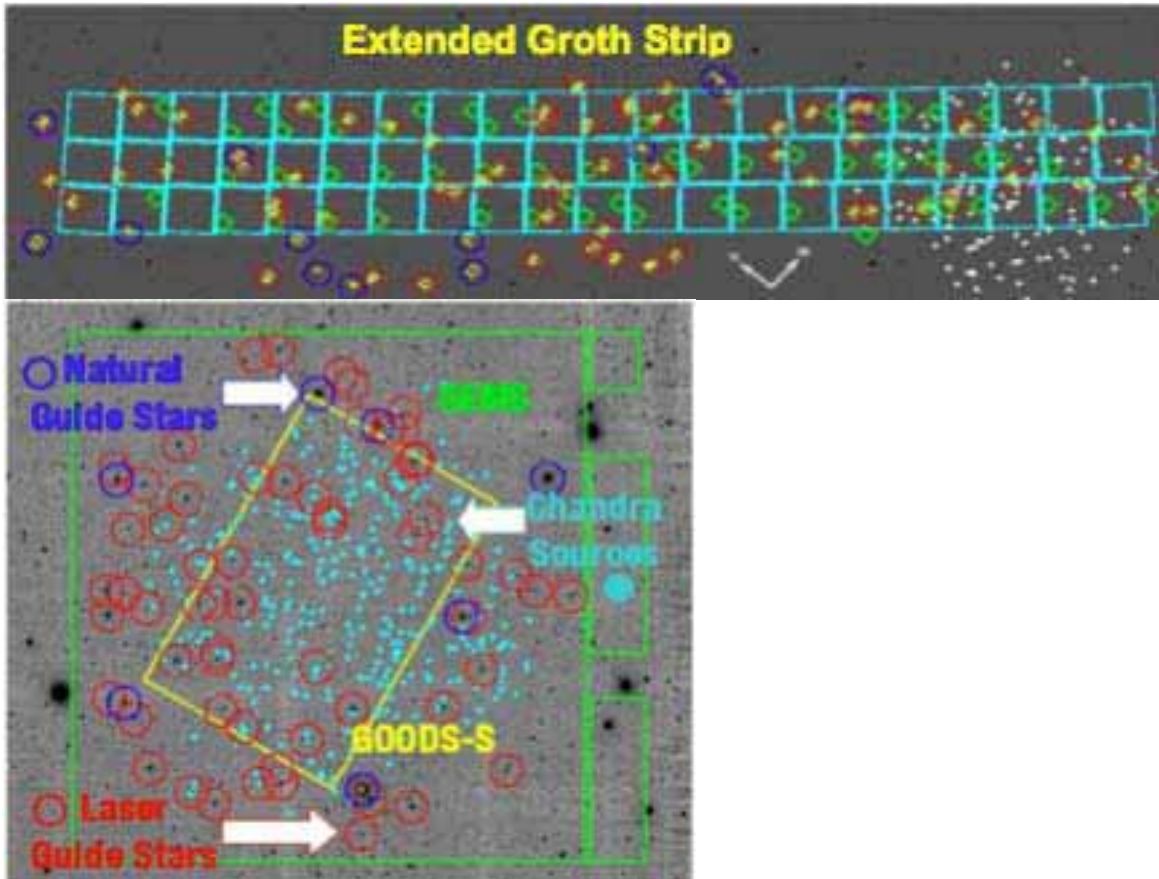


Fig. 2.8 Observing coverage of the new Extended Groth Strip (EGS) field (top) and the GOODS South region (bottom), both already observed with multi-band HST ACS imaging. The EGS is 10x60 arc min; the GOODS-S is 10x15 arc min. Not shown are the GEMS field (30x30 arc min) and the COSMOS field (84x84 arc min). Both the EGS and GOODS-S fields have relatively few available natural guide stars (stars with $V < 13$ mag, circled in blue). Red circles show the vastly larger coverage possible with LGS AO centered on much fainter tip-tilt stars ($V < 18$ mag). The white dots in the EGS (right) and the blue dots in GOODS-S field show the density of relatively rare Chandra X-ray sources. Non-X-ray galaxies (difficult to depict on this scale) are at 100x greater densities. The EGS image above also shows the locations of HST NICMOS-3 images (green diamonds)

Solar System planetary science

Overview

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

Software development

The AIDA deconvolution algorithm, its source code, and a friendly interface was publicly released in 2006. A paper describing the method and its application in a large range of fields (astronomy and medical science) is in press in JOSA (Hom et al., 2007). A few astronomical applications are presented in this progress report and it should be noted that this algorithm is much faster (and less cumbersome) than MISTRAL. Deconvolving one 512×512 Titan image, for example, took only 15 min with AIDA (Linux OS, Pentium 4@ 2 Ghz), and would have taken a full day with MISTRAL. AIDA was recently released for Intel iMacs (our desktop machines), and hence we expect to test it on large images (such as Uranus) and OSIRIS datacubes during the upcoming CfAO year. Meanwhile, we have successfully applied it to some non-AO Neptune images in the mid-infrared (LWS Keck data), and on SCAM AO images of Io.

UCB students Marshall Perrin and Conor Laver installed the OSIRIS pipeline in Berkeley, and extensively helped the UCLA team and Keck observatory in debugging the system. They tested the code, optimized several routines, and are now working on the development of other routines. Both students (M. Perrin is now a postdoc, and will work with the UCLA group) have OSIRIS data and hence are highly motivated to get it to work. The involvement of these two CfAO Berkeley students has been quite helpful to the OSIRIS staff, CfAO, and the community at large.

Asteroids

It was only when the first images of the asteroid (243) Ida captured by the Galileo spacecraft revealed the presence of a small satellite named Dactyl, that the existence of binary asteroids suggested by Andre (1901) was unambiguously confirmed. The advent of high angular resolution imaging provided by instruments such as ground-based telescopes equipped with adaptive optics (AO) systems, and also by the Hubble Space Telescope, permitted the discovery of new visual binary asteroids (Noll, 2006; Richardson and Walsh, 2006)³. At the time of writing, more than thirty systems have been imaged, but the number of suspected binary asteroids is significantly higher (~120) since many of them display mutual event signatures (Behrend et al. 2006, Descamps et al. 2007) and/or multi-period components (Pravec and Harris, 2006) in their lightcurves. Despite recent simulations involving catastrophic collisions (Durda et al. 2004), fission via the YORP effect (Cuk et al. 2005), and splitting due to tidal effect with a major planet (Walsh and Richardson, 2006), the formation of most multiple asteroidal systems is not yet understood. Insights into these binary systems, such as the orbital parameters of the satellite, the size and shape of the components of the system, the nature of their surface, and their bulk density could provide a better understanding of how these multiple asteroidal systems formed.

Over the past few years, the de Pater group has focused its attention on binaries located in the main-belt and Trojan swarms which have been discovered visually. The group initiated an

³ References are in Section VIII.1A Center Publications

intensive campaign of observations from 2003 through 2006 combining the high-resolution capabilities of various 8m-class telescopes (UT4 of the Very Large Telescope, W.M. Keck-II and Gemini-North) equipped with adaptive optics systems that allowed resolution of the binary system. This project is part of the LAOSA (Large Adaptive Optics Survey of Asteroids, Marchis et al. 2006c), which aims to discover binary asteroids and study their characteristics using high angular capabilities provided by large aperture telescopes with AO systems. Already published is a complete analysis of the orbit, size and shape of two doublet asteroidal systems (composed of two similarly sized components): (90) Antiope (Descamps et al., 2007) and (617) Patroclus (Marchis et al., 2006). The same analysis was performed for binary asteroids with a small satellite, which resulted in the publication of a complete analysis of 12 systems (Marchis et al., 2005, 2007ab). This work has revealed a great diversity in the orbits of binary main-belt asteroids, which suggests a different origin and evolution. The bulk density calculated using the orbital parameters of the satellite orbit is quite variable depending on the taxonomic class and, in most of the cases, indicates that the primary has a significant macro-porosity (>30%), suggesting a rubble-pile interior.

Thanks to the improvement in quality of recent AO systems NACO at the VLT and NGWFS at Keck, smaller and closer moonlet companions around main-belt asteroids can now be detected. A direct consequence of the telescope's improved sensitivity was the discovery of the first asteroidal system composed of 2 moonlets (Marchis et al., 2005) in February 2005. Two moonlets, called Remus (7 km) and Romulus (4 km), orbit at 700 and 1400 km around a 280-km size and elongated primary named (87) Sylvia. The second triple system (45) Eugenia was also discovered by our group and announced in March 2007 (Marchis et al., 2007). The orbit of the innermost moonlet remains uncertain. Because the orbital parameters of various binary systems are well known, it should be possible to optimize spectroscopic observations of the primary and the moonlet using new integral field imagers (i.e. OSIRIS at Keck) or a slit spectrograph combined with AO systems (NIRC2 at Keck). A spectroscopic comparison will help to constrain the origin of the system, to learn if the moonlet was captured and has a different composition than the primary, or if it is a subsequent fragment of a large collision which also formed the primary.

Io

After the initial discovery of the forbidden SO emission on Io-in-eclipse with NIRSPEC (de Pater et al. 2002), Conor Laver reduced data taken over several years and showed, as in the initial dataset, rotational temperatures of the gas of many 100's K (Laver et al. 2007a). Detailed analysis of the initial discovery spectra suggests that the SO gas is directly released from a volcanic vent, at about 1500 K. To further investigate the relation between SO gas and volcanic activity, Io was observed in eclipse in Nov. 2002 with NIRSPA0, using Callisto for wavefront sensing. Although the SO line during that time was extremely weak, it was clearly detected in several of our scans. This was extremely challenging both in experiment and analysis, but the results were exciting and the subsequent paper has been accepted for *Icarus* (de Pater et al. 2007a).

Io was observed with the OSIRIS imaging spectrometer in April and June 2006. A volcanic outburst was detected in Io's northern hemisphere on 17 April 2006, which was still active in June 2006. The eruption was located in Tvashtar Catena, ~100km southeast of the Feb 2000 eruption. This was the first time anyone has obtained spectra of an eruption with an integral field detector, and a temperature of $1240 \pm 4\text{K}$ was derived from the spectra (independent from H and K band spectra), over a surface area of $60 \pm 5\text{km}^2$, providing a total thermal output of $7.7 \pm 0.9 \times 10^{12}\text{W}$. A paper has been submitted (Laver et al. , 2007b). (Fig. 2.9)

Conor Laver is currently working on a paper to identify the SO₂ ice coverage on Io's surface from the Io OSIRIS datacubes. His involvement in improving and debugging the OSIRIS pipeline has been triggered by these datasets, which form the core of his Ph.D. thesis.

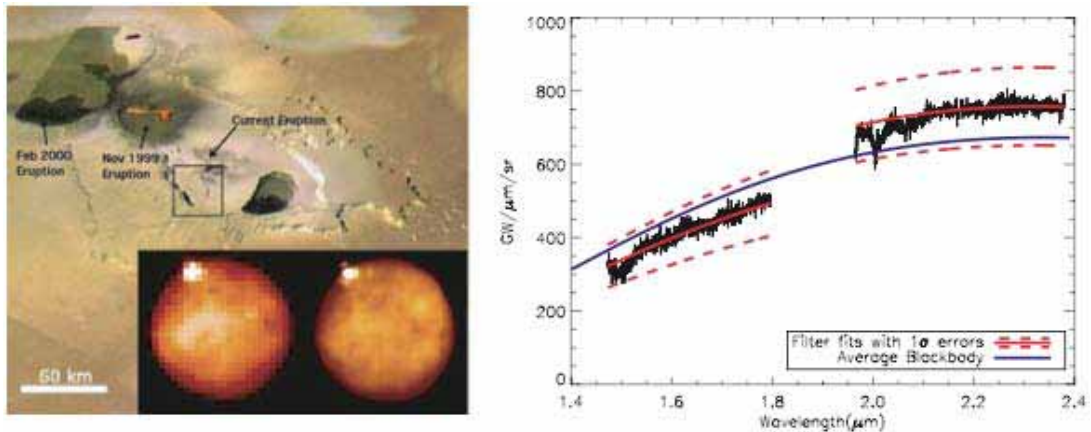


Figure 2.9. [left] A mosaic of a high resolution image taken by Galileo on its I25 flyby in November 1999 (Eruption site) and a low resolution image taken in July 1999. The estimated position of the April 2006 eruption in Tvashtar patera is shown as a 1-sigma error box. Our OSIRIS AQ data are shown inset with (left) the low resolution (0.05" pixels) initial detection on 17 April 2006 and (right) the high resolution (0.02" pixels) image taken on 2 June 2006. [right] Extracted H and K band spectra of Tvashtar on 2 June 2006. The lighter solid lines show the individual filter fits with their 1-sigma photometric errors (dashed lines). Also plotted is the blackbody curve for the averaged temperature (1240K) and area (56 3qu.km) estimates from the data.

Titan

AO observations of Titan relate to the de Pater's group's long-term goal of better understanding Titan's atmosphere, its seasonal cycles (haze migration and cloud formation) and the composition of its surface. The problems of mapping Titan's surface reflectance and haze vertical structure are linked. Titan's surface can be probed in near-infrared 'windows' between methane bands, but the radiation will not immediately reveal surface composition, since sunlight reflected from the surface is significantly modified by haze scattering and methane absorption in the atmosphere, neither one of which is known 'a priori'. Over the past year observations of Titan have continued with Keck (OSIRIS and NIRC2) and the VLT (with SINFONI). The Keck data have been largely reduced and analyzed.

Mate Adamkovics has continued to improve his radiative transfer (RT) algorithm to invert 3D image data-cubes of Titan into a 3D haze distribution. This algorithm was discussed in some detail in last year's report. He just finished a paper for Science (Adamkovics et al. 2007), which specifically deals with Titan's troposphere. A paper describing the model in detail, and applying this model to all datasets accumulated from Keck and the VLT over the past decade is in preparation.

Jupiter

Jupiter's ring was imaged with Keck AO in the L' and K' bands during the 2002-2003 ring plane crossing. Wavefront sensing was performed using Callisto. During the past year much progress has been made in the analysis of the K' band data (the L' data and Callisto were published in Wong et al. 2006). The ring is clearly detected: the main ring, halo, as well as the Amalthea gossamer ring (Fig. 2.10a). The latter ring shows the bright top and bottom edges as shown by alileo data.

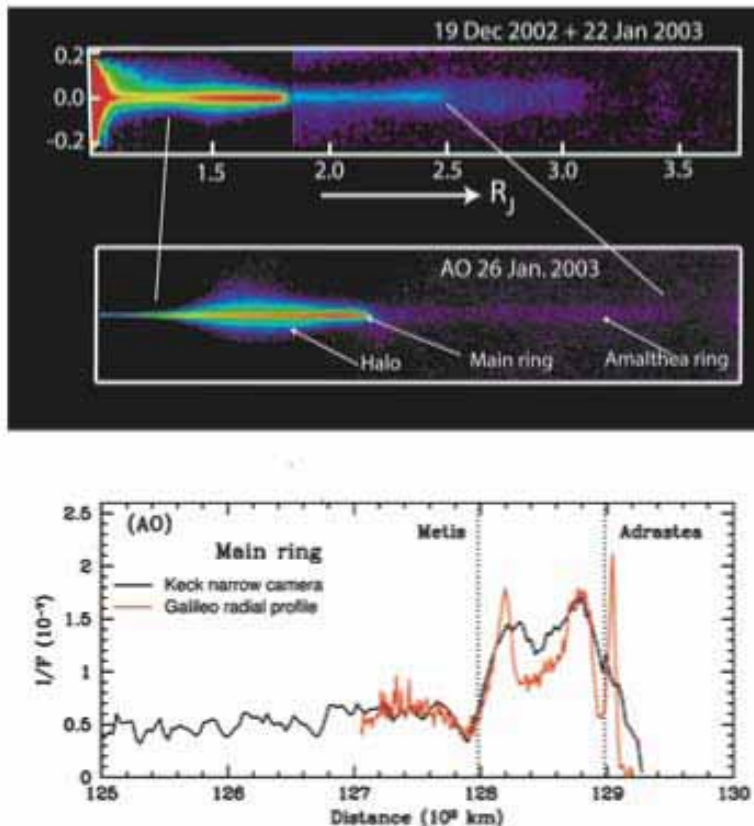


Figure 2.10. [top] Jupiter's rings: The top panel shows a conventional infrared image of the jovian ring, obtained on UT 19 Dec. 2002 and 22 Jan. 2003 (data are combined). The spatial resolution is about 0.7". The bottom panel shows the AO image from 26 Jan. 2003. The white lines indicate which portion of the rings were imaged (main ring, halo and Amalthea ring). [bottom] A high resolution radial profile of Jupiter's main ring, obtained by onion peeling the edge-on profile from the image obtained with the AO NIRC2 narrow camera. The profile was smoothed radially over 0.03". Superposed is a visible light Galileo profile at low phase angles, normalized to the intensity of the Keck profile's inner extension of the main ring. 1 jovian radius is 71,492 km. Note that the portion in the graph is at the tip of the main ring in the AO image. (de Pater et al., 2007)

Since Jupiter's rings are optically thin, edge-on, and presumably cylindrically symmetric, the images could be inverted by using an "onion-peel" deconvolution method (Showalter et al. 1987; de Pater et al. 1999, 2004, Verbanac et al. 2005). After applying this technique to the AO data, the radial structure of the ring was compared to a visible light Galileo profile. It is remarkable how well Keck performs in comparison with Galileo, a spacecraft which at the time was in orbit around Jupiter and observed the system at a wavelength 4 times shorter than that at Keck. Preliminary analysis of these data shows that the main ring, located between the orbits of the moons Metis and Adrastea, is redder than its inward extension, suggestive of the bulk of "parent-sized" material to be located in this ring. A paper is being prepared.

Uranus

Last year a detailed report was provided on the De Pater group's Keck observations of Uranus, and two substantial papers had been submitted: one on the discovery of the inner dust ring, now officially named the ζ ring, and another on discovering that Uranus's new outer ring system is very similar to that of Saturn (de Pater et al. 2006). The observations of the planet have continued, both to track changes in its atmosphere, and to obtain data at different ring inclination angles. The dataset at a ring inclination angle of $\sim 3^\circ$, obtained in July 2006, shows perhaps a hint of the outer ring; if true, the intensity level is just below the published upper limit.

Massive black hole at the center of our Galaxy

The center of our Milky Way Galaxy is now known to contain a black hole with more than three million solar masses, and thus represents a very nearby opportunity for studying the physics and astrophysics of black holes in galaxy cores. Technically, the Galactic Center presents challenges that range from observational, due to the lack of a bright natural guide star at optical wavelengths,

to analytical, due to the crowded stellar field at near-infrared wavelengths. We therefore are studying Adaptive Optics performance on this field with a variety of different systems (Keck vs. Gemini; NGS vs. LGS) from the point of view of point spread function quality, overall Strehl, stability, and anisoplanatism. In addition we are investigating the astrometric and spectroscopic accuracies that can be achieved in such a crowded stellar field. These results will be useful for a number of different applications and are of large interest to the general CfAO community.

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

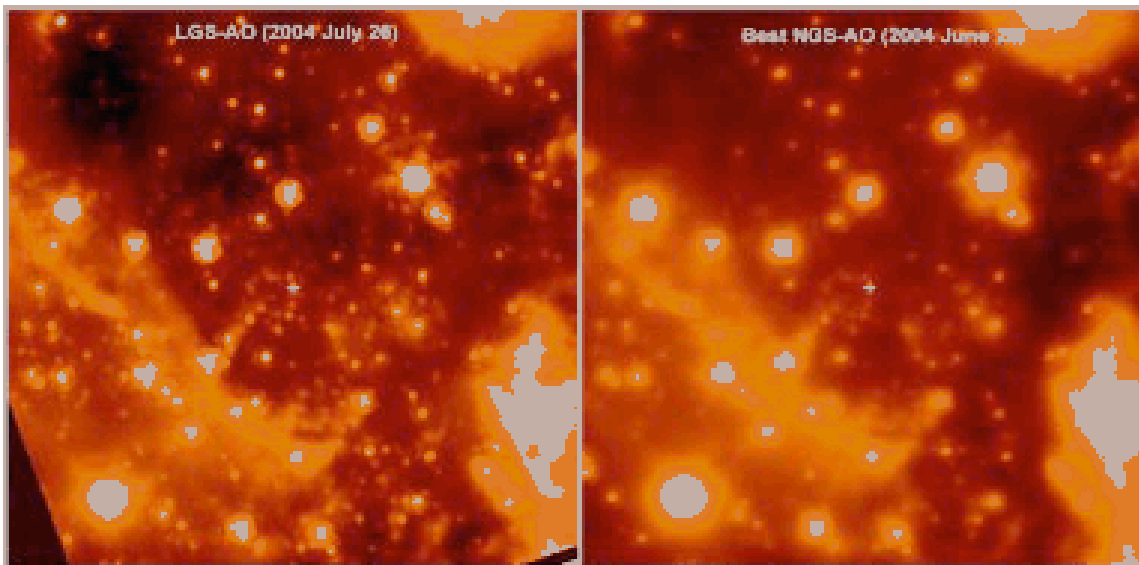


Figure 2.11: A comparison of the first LGS-AO image (left) and the best NGS-AO image (right) taken with the W. M. Keck II 10 m telescope in the L'(3.8 μm) photometric bandpass of the central $7.''5 \times 7.''5$ of our Galaxy. In both images, the cross denotes the location of the central supermassive black hole and the orientation is North up and East to the left. The LGS-AO image has a Strehl ratio that is a factor of two higher than that obtained in the NGS-AO image; furthermore, the LGS-AO image resulted from an exposure time of only 8 min, a factor of ~ 20 less than the comparison NGS-AO image. The LGS-AO system has therefore dramatically improved the image quality that can be obtained on the Galactic Center with the Keck telescope. Without AO the crucial stars that are used to reveal and study the central supermassive black hole are not even detectable

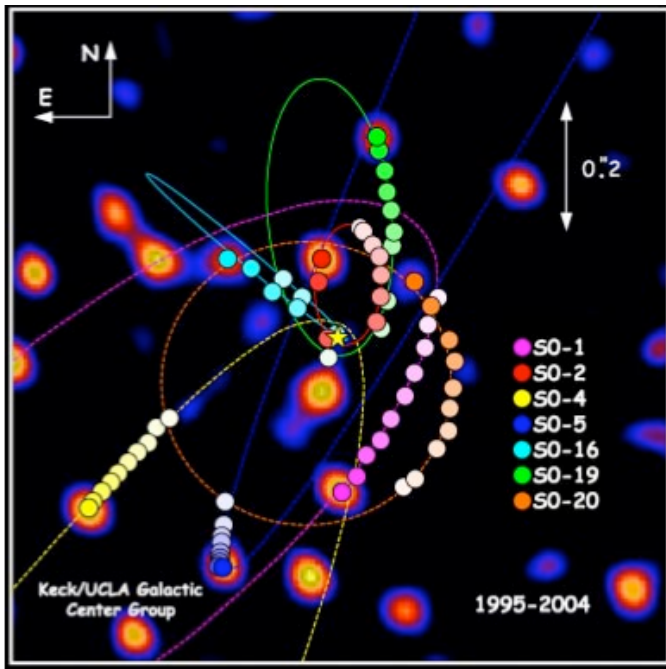


Figure 2.12: Astrometric positions (annual averages shown) and orbital fits for several stars within the central square arcsecond of the Galaxy, overlaid on a recent image. With multiple orbits, the central black hole's properties can be strongly constrained (position, velocity, and mass) and the ensemble kinematics of the cluster can be directly studied.

Progress report for Year 7

Milestone 1: Submit proposals to use Keck AO systems for proposed Year 8 work

Proposal submitted and awarded time in May, June, and July 2007 to conduct LGS-AO Keck observations of the Galactic center.

Milestone 2: Conduct AO observations on Galactic Center in imaging and spectroscopic modes in Summer '06

Successful LGS-AO HK'L' imaging and spectroscopic observations were conducted in May, June and July 2006.

Milestone 3: Begin Analysis on Arches (dynamics and IMF)

We presented the first measurement of the proper motion of the young, compact Arches cluster near the Galactic center from near-infrared LGS adaptive optics (AO) data taken with the recently commissioned laser-guide star (LGS) at the Keck 10-m telescope. The excellent astrometric accuracy achieved with LGS-AO provides the basis for a detailed comparison with VLT/NAOS-CONICA data taken 4.3 years earlier.

Milestone 4: Finish Analysis on IRS13

All observations for the IRS 13 proper motion study have been completed and analysis is in progress. The data have revealed that several sources do not appear point like. This can be interpreted in one of several ways. First, each resolved source may be several stars crowded together. Or these sources may be a single star with high stellar winds that produce a resolved bow shock. The proper motion analysis that is in progress will shed light on this subject and allow us to identify which of the stars are members of the IRS 13 cluster.

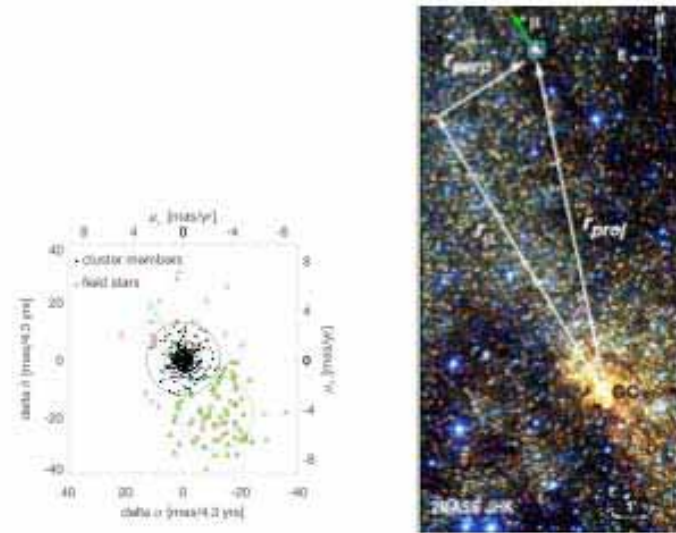


Figure 2.13. Proper motion of the Arches cluster in the cluster reference frame. Keck LGS-AO data revealed that the cluster moves to the North-East with respect to the field population (left). The cluster motion relative to the GC is illustrated on the 2MASS image (right).

Milestone 5: Improve analysis on orbits to push for detection of non-Keplerian motion

We carried out a detailed study of the astrometric biases contributing to both the relative and absolute astrometric precision. With LGS-AO, we have improved our relative astrometric precision by an order of magnitude (from 2 mas to 0.2 mas). The effects of differential atmospheric refraction, pixelization, and centroiding shifts from unresolved neighboring sources on the position accuracy were quantified from observations and simulations. The centroiding accuracy was shown to improve with the total number of observed frames. An improved distortion solution provided by Brian Cameron was implemented. The results show significant improvement over previous solutions.

Milestone 6: Analysis of Sgr A* lightcurve (continuously variable or punctuated flares)

We report the first time-series measurements of Sgr A*-IR's broadband infrared color. Using the LGS AO system on the Keck II telescope, we imaged Sgr A*-IR, in the broadband filters H (1.6 m), K' (2.1 m), and L' (3.8 m) every 3 minutes over the course of 120 minutes, during which time the Chandra X-ray Observatory was also monitoring the Galactic center. During our observations, Sgr A*-IR's flux density showed a wide range of values (2 to 12 mJy at 2.1 μm), which are associated with at least 4 peaks in the infrared emission and are among its highest infrared flux density measurements. All our near-infrared color measurements are consistent with a constant spectral slope of $\alpha = -0.9 \pm 0.2$ ($F_\nu \sim \nu^\alpha$), independent of intensity, wavelength, time, or outburst. Assuming that the infrared wavelengths probe synchrotron emission, we interpret the lack of variation in the infrared spectral index as an indication that the acceleration mechanism leaves the distribution of the bulk of the electrons responsible for the infrared emission unchanged. During our coordinated infrared observations, no elevated X-ray emission was detected. The lack of X-ray variation during the significant infrared variations reported here indicates that one may not be able to connect the infrared and X-ray emission to the same electrons. We suggest that while the acceleration mechanism leaves the bulk of the electron energy distribution unchanged, it generates a variable high-energy tail

Milestone 7: Publish Young Star Proper Motions

We present new proper motions for the massive, young stars at the Galactic Center, based on 10 years of diffraction limited data from the Keck telescopes. Our proper motion measurements now have uncertainties of only 1-2 km/s and allow us to explore the origin of the young stars that reside within the sphere of influence of the supermassive black hole whose

strong tidal forces make this region inhospitable for star formation. Our precise proper motions allow us, for the first time, to determine the orbital parameters of each individual star and thereby to test the hypothesis that the massive stars reside in two stellar disks. Of the 26 young stars in this study that were previously proposed to lie on the inner, clockwise disk, we find that nearly all exhibit orbital constraints consistent with such a disk. On the other hand, of the 7 stars in this study previously proposed to lie in the outer, less well-defined counter-clockwise disk, 6 exhibit inclinations that are inconsistent with such a disk. For stars in the inner disk that have eccentricity constraints, we find several that have lower limits to the eccentricity of more than 0.4, implying highly eccentric orbits. This stands in contrast to simple accretion disk formation scenarios which typically predict predominantly circular orbits.

Milestone 8: Publish stellar variability

We report the results of a diffraction-limited, photometric variability study of the central $5'' \times 5''$ of the Galaxy conducted over the past 10 years using speckle imaging techniques on the W. M. Keck I 10 m telescope. Within our limiting magnitude of $m_K < 16$ mag for images made from a single night of data, we find a minimum of 15 K[2.2 micron]-band variable stars out of 131 monitored stars. The only periodic source in our sample is the previously identified variable IRS 16SW, for which we measure an orbital period of 19.448 ± 0.002 days. Our data on IRS 16SW show an asymmetric phased light curve with a much steeper fall time than rise time, which may be due to tidal deformations caused by the proximity of the stars in their orbits.

Milestone 9: Publish Galactic Center distance paper

This year we have focused on understanding the astrometric biases that can change this value from 7.2 all the way up to 9.0 kpc. We are now confident in our unbiased estimate and will publish this result by fall 2007.

Milestone 10: Analysis of integral field spectroscopy of the galactic center with OSIRIS

The use of integral field spectroscopy has greatly increased our efficiency in obtaining spectra at the Galactic Center. The spectra obtained in 2006 have allowed us to separate the late-type giants from the young B type stars, resulting in the five newly identified young stars. The additional identification of young stars further emphasizes the paradox of youth problem of star formation under the influence of the black hole.

Theme 3: Extreme Adaptive Optics (ExAO): Enabling Ultra-High Contrast

Astronomical Observations

Introduction

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

In Year 5, the CfAO team completed the conceptual design of an ExAO system for the Keck Observatory and subsequently competed for and was awarded a contract from the Gemini Observatory for a similar ExAO system design study. The CfAO design team expertise was significantly augmented for the Gemini design study by participants from additional institutions in the US and Canada. During Year 6, this partnership completed the Gemini ExAO system design study and delivered to Gemini a comprehensive conceptual design report and a proposal for construction of the instrument. Following a series of technical and programmatic reviews, this proposal – now called the Gemini Planet Imager (GPI) was selected for funding by Gemini, fulfilling one of the overall ExAO theme goals and objectives – obtaining the additional funding required for an instrument capable of imaging extrasolar planets. Figure 3.1 shows a simulated GPI image.

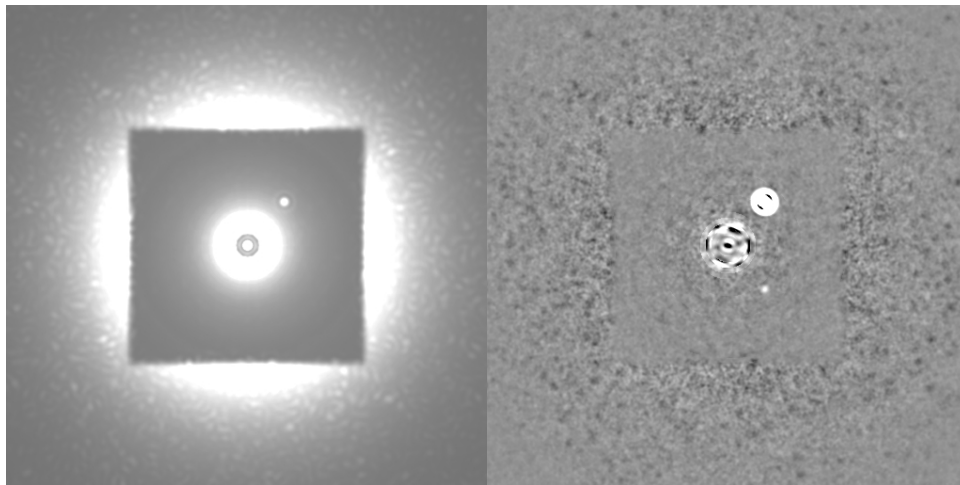


Figure 3.1: Simulated 2hr GPI exposure of a K7V star at a distance of 10 pc, age=100 Myr, with 5 M_J ($\Delta H=12$) and 1 M_J ($\Delta H=17.5$) companions at 4 AU separation. Left: direct narrowband 1.59 μm image with no post-processing. Right: image after spectral differencing. Simulation includes both dynamic atmospheric errors (extrapolated from a 10 second exposure) and quasi-static instrumental errors including Fresnel optics effects and chromaticity.

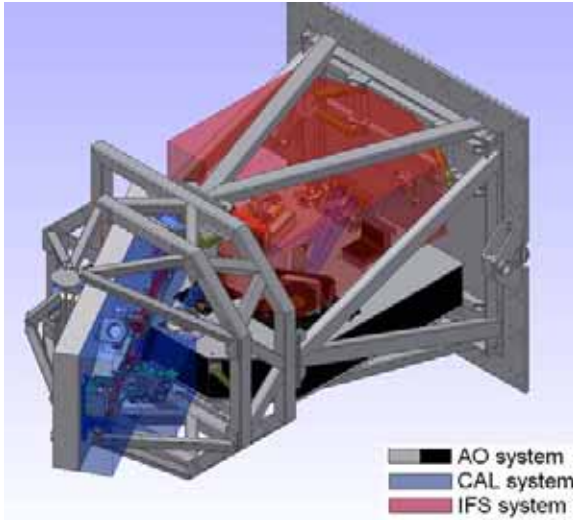


Figure 3.2: CAD rendering of the GPI instrument with covers and electronics racks removed. The plate on the right, 1.2 meters on a side, mounts to the Gemini telescope.

In Years 7-10, ExAO theme efforts include risk reduction and the study of key technologies for ExAO: MEMS properties, wavefront sensing and reconstruction without systematic errors, optimal coronagraph architectures, and precision wavefront calibration. We continue to demonstrate some of these technologies in the Laboratory for Adaptive Optics at UCSC, JPL and the American Museum of Natural History. We also continue to support ongoing programs in high-contrast observations at Lick and Keck observatories. The CfAO supports science planning for GPI to enhance the ability of the scientific community to utilize this instrument and prepare the ground for Center scientists to carry out a large-scale Gemini survey in 2011. We also continue to support new ExAO concepts and techniques – for example, a project to use a 1.5-meter off-axis portion of Palomar 5-meter telescope along with the existing Palomar AO system to produce a AO system with very high Strehl ratios, allowing ExAO concepts such as spatially-filtered wavefront sensors to be tested.

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

ExAO Theme Accomplishments

High-contrast science with current AO systems

The team led by Andrea Ghez at UCLA is continuing to probe star and planetary system formation. A major project in this area is measuring the complete 3-dimensional orbits of very low mass binary stars. Currently, the masses of the smallest stars are only very poorly known,

calibrated from theoretical models of stellar properties and a handful of actual observations. This is especially true for the “brown dwarfs” - transitional objects between stars and planets that are too small to successfully burn hydrogen as stars do.

Using the power of the Keck AO system, the UCLA group is now directly measuring the masses of very low mass binary stars (Konopacky et al 2007) and brown dwarfs. Masses can be directly measured through studies of the orbits of binary stars, but low-mass binaries that move fast enough to be studied in a reasonable time will automatically be very compact – the two components too close to be studied without AO. In addition, measuring the orbit from only the apparent positions of the stars leaves an ambiguity from the three-dimensional orientation of the binary relative to the line-of-sight to the Earth. The UCLA group is combining high spatial resolution AO images (measuring the projected positions of the two members of the binary system) with spatially resolved IR spectra (measuring the spectral type and line-of-sight Doppler shift of the individual stars) to completely map out their orbits. This in turn will lead to the first accurate determination of the masses of the smallest known stars, including objects that may be below the dividing line between stars and failed “brown dwarfs”. These measurements will then calibrate theoretical evolutionary calculations.

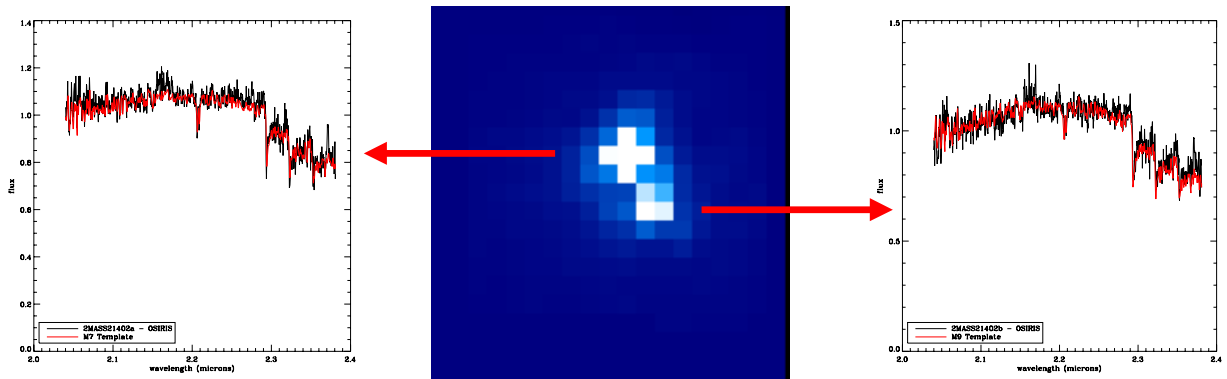


Figure 3.3: OSIRIS collapsed image (center) and extracted spectra for both components of the very low mass binary 2MASS2104+16. Pixel size is 0.025 arcseconds.

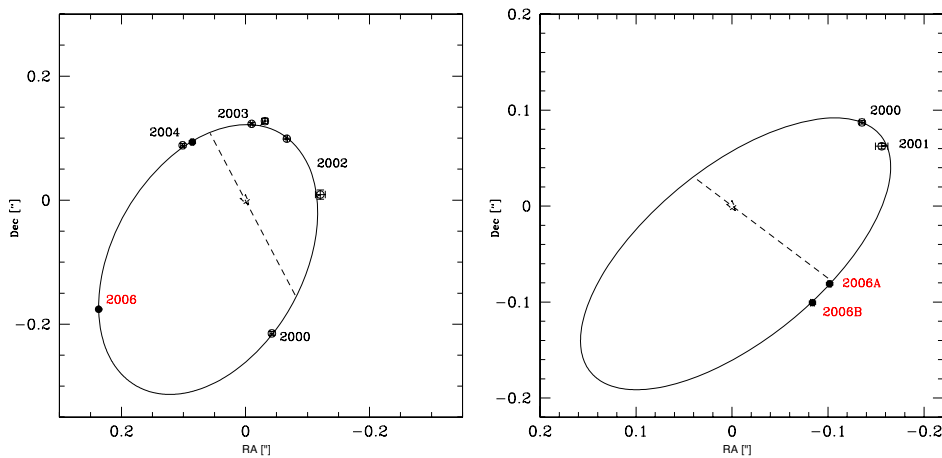


Figure 3.4: (Left) Orbital solution for the brown dwarf binary 2MASS0746+20. New astrometric measurement from Keck LGS AO is highlighted in red. This datapoint has allowed a measurement of the

mass to better than 1%. Right: First orbital solution for the very low mass binary 2MASS 2206-20. Measured mass is now 0.13 solar masses.

The team led by James Graham at UC Berkeley is continuing a program of observing debris disks around nearby stars with Keck AO and the Hubble Space Telescope, and a survey of young protoplanetary dust disks around Herbig Ae/Be stars using Lick AO polarimetry. Debris disks are the extrasolar analogs of our Zodiacal and Kuiper dust belts. The objects studied to date are young, massive dust disks, signposts of the transitional phase from protoplanetary disk to mature solar system. In Year 8, Graham and his student, Michael Fitzgerald, published multiwavelength observations of the dust disk surrounding the young star AU Mic. (Fitzgerald et al 2007). Observations of these dusty disks at multiple wavelengths constrain the optical properties of the dust, allowing inferences about whether the dust grains are the remnant of the original interstellar cloud that formed the star or the debris from comet and planetesimal formation in a young solar system (Figure 3.5).

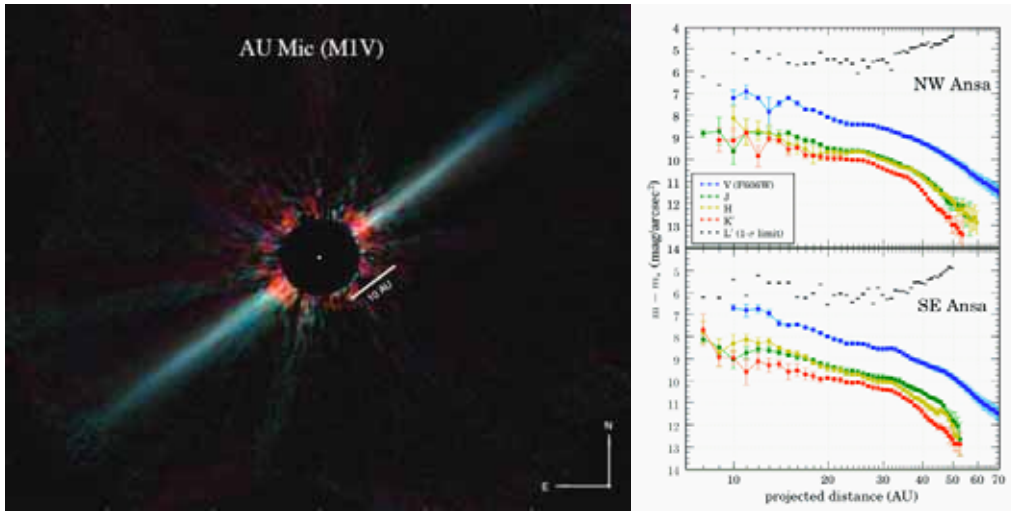


Figure 3.5: *Left:* Four-color composite ($JHKL'$) of the AU Mic debris disk using Keck AO/NIRC2 coronagraphy (Fitzgerald et al. 2007). The blue color gradient indicates an outer component composed of small grains. *Right:* AO surface photometry showing the blue color of the disk.

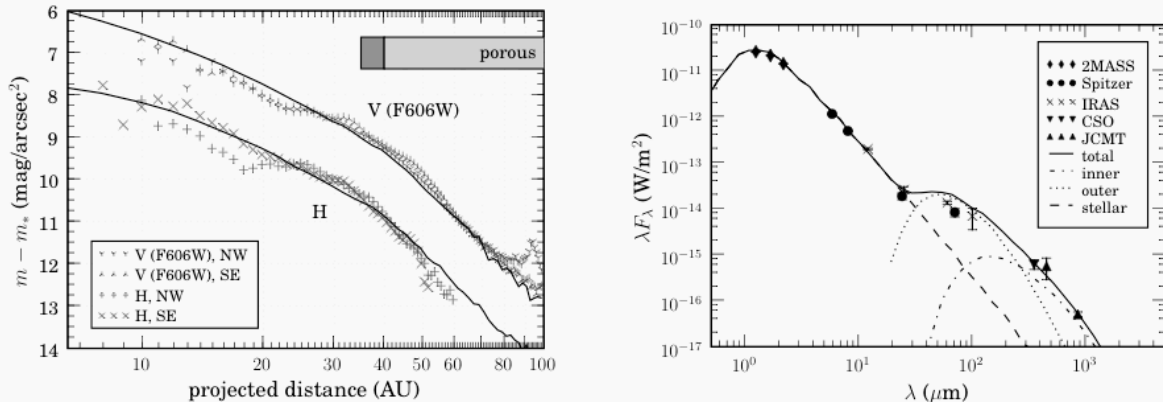


Figure 3.6: *Left:* Model fit to the scattered light and SED of AU Mic (Fitzgerald et al. 2007). The surface brightness profiles from Figure 3.5 are shown along with surface brightness profiles from the best-fit model. The gray boxes above the profiles represent the grain locations in the model; the dark region indicates the inner region of larger grains, while the smaller scatterers are in the lighter zone outside. *Right:* The model SED along with photometry of AU Mic. In this model, the smaller grains cause the bulk of the

scattered light and the mid-IR emission, while the larger grains reproduce the long-wavelength end of the SED.

The Berkeley group is also studying the younger massive Herbig Ae/Be stars using the Lick Laser Guide Star AO system. Marshall Perrin has completed an imaging polarimetry survey at Lick of the northern hemisphere Herbig Ae/Be stars, and is now working on quantifying the distribution of circumstellar material on scales of ~ 100 AU with detailed radiative transfer modeling, carried out in collaboration with Center member Gaspard Duchene (visiting Berkeley from France.) Figure 3.7 illustrates the initial stages of finding a model fit for the system PDS 144 N (Perrin et al. 2006)⁴.

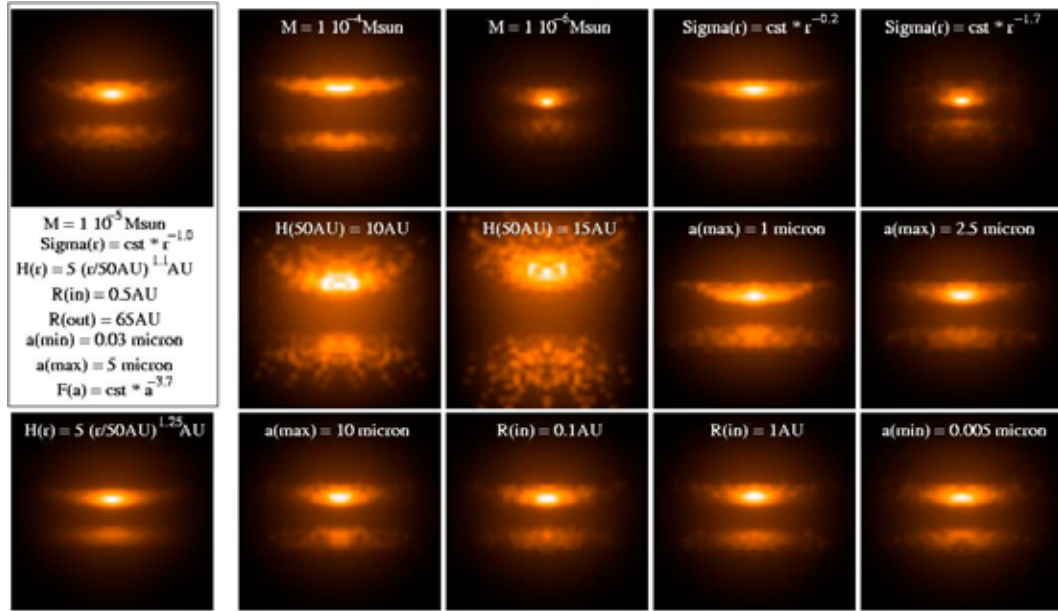


Figure 3.7: A suite of model H band images of protoplanetary disks for comparison with the AO observation of the Herbig Ae/Be star PDS 144 N (Perrin et al. 2006). The top left panel shows the baseline model, with parameters listed below. Additional panels show the effect of modifying a single parameter. Most of the parameters explored here result in very different apparent morphology, and only a small fraction of the entire parameter space is capable of reproducing the observed image.

Science Case for Gemini Planet Imager

CfAO member James Graham at UC Berkeley serves as Gemini Planet Imager (GPI) Project Scientist and has been leading the development of the GPI science case. The science case currently includes three main themes for exoplanet research. First, to assemble a statistically significant sample of exoplanets that probes beyond the indirect searches and quantifies the abundance of solar systems like our own, studying the fossil remnants of planet formation to constrain current theories that make different predictions for populations in the outer parts of solar systems.

Second, to begin spectroscopic characterization of extrasolar planets. GPI will produce spectra of individual planets from 1-2.4 μm at resolution $\lambda/\partial\lambda \cong 45$. Simulations and extrasolar planet models show that this is sufficient to determine planet temperature/mass/age properties to $\sim 10\%$

⁴ See Publications Section - Publication # 61

accuracy, and to potentially distinguish between planet models with different compositions. Figure 3.8 shows a representative planet model used to construct synthetic GPI colors and Figure 3.9 shows the accuracy with which GPI measurements can constrain planet mass, temperature, and age.

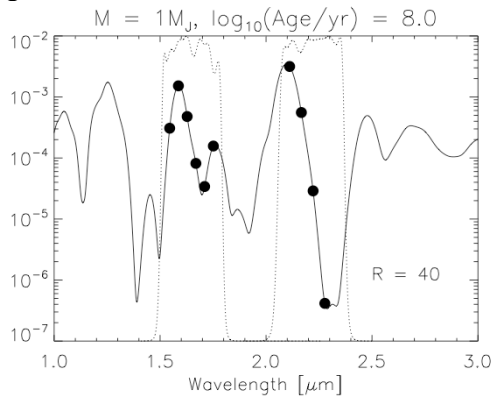


Figure 3.8 The spectrum of a 100 Myr, 1 Jupiter mass planet from Burrows et al. (2003) smoothed to a spectral resolution of 40. The dots represent sampling of the smoothed spectra in non-overlapping spectral channels. In this example 10 independent flux measurements are made. In the current analysis for this example these are combined to form to five colors in H and three colors in K. The dotted lines represent the transmission of the GPI H and K filters, showing the extent of the atmospheric windows.

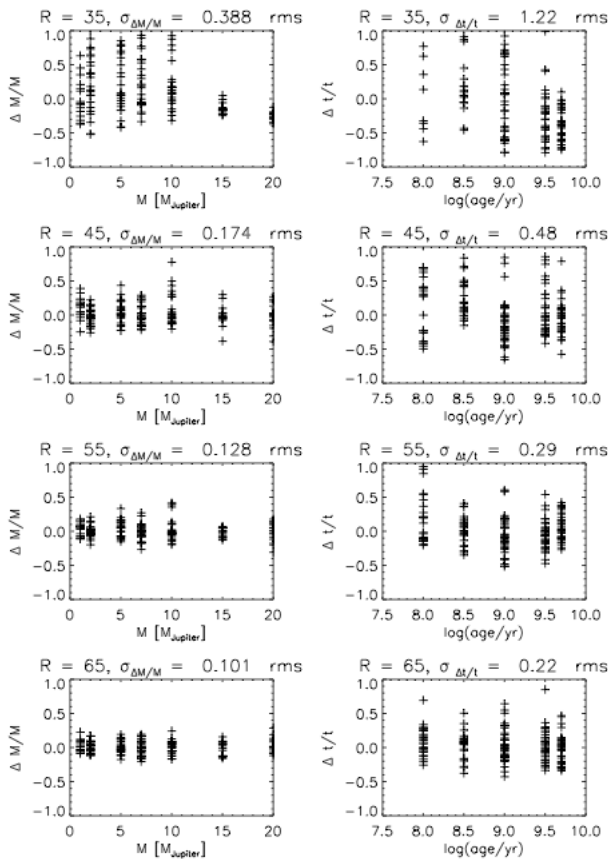


Figure 3.9: Results of quadratic regression analysis showing the residual between planet properties based on colors in *H* and *K* bands. Fractional residuals for planet mass are shown in the right column, fractional residuals for age are on the left. The title of each plot lists the spectral resolution and the rms residual. All these results are for $SNR = 10$ per color. The ability to discriminate both mass and age increases monotonically with increasing spectral resolution.

A third major science area for GPI is extending the study of circumstellar dust disks from the current target set – young stars with very massive debris disks – to more mature sunlike stars. GPI will combine extremely precise AO correction with a polarimetric mode that can distinguish the polarized light scattered by a dust disk from unpolarized artifacts (Figure 3.10). Prof. Graham’s group has extensively developed this technique at Lick Observatory and are now studying how to incorporate it into GPI.

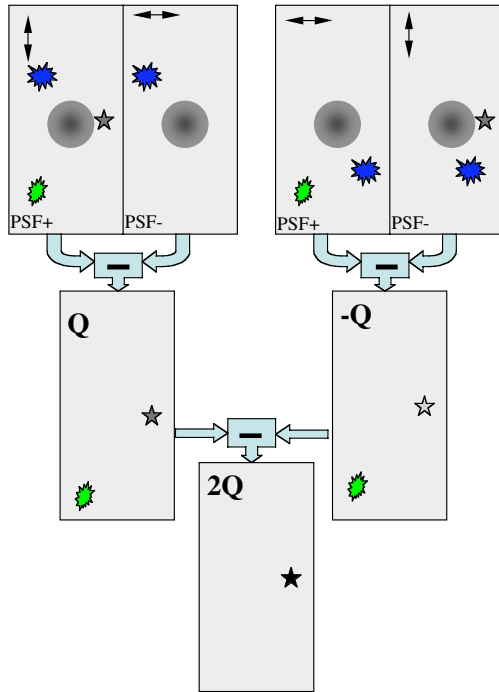


Figure 3.10: Speckle subtraction in dual-channel differential polarimetry. Each raw image (top row) consists of two half-field sub-images (PSF+ & PSF-), in perpendicular polarizations, denoted by two-headed arrows; the waveplate has been rotated by 45° between the left hand & right hand pair. An unpolarized central source (grey) surrounded by an atmospheric speckle (blue spot at 11 o'clock on the left and 5 o'clock on the right) and a non-common path speckle (green spot at 7 o'clock) and a polarized astrophysical source (grey five-pointed star at 3 o'clock). Single subtractions (second row) reveal the polarized astrophysical source, remove the unpolarized halo, cancel common-path speckles but leave non-common-path speckles (green) intact. Non-common path speckles have the same sign in both single-difference images, while the astrophysical polarized signal has opposite signs in the Q and $-Q$ images, due to the waveplate rotation. Therefore, the double difference (third row) cancels non-common-path speckles, leaving only astrophysically polarized light.

In Years 9-10, the science focus in anticipation of GPI will be on target selection and preparation for a large-scale survey. The Gemini Observatory plans to devote 100-200 nights of telescope time to a systematic survey of 1000+ stars using the GPI instrument – an extremely significant investment for a major observatory. The team for this survey will be selected competitively (as with Gemini’s current NICI instrument.) Although the survey itself won’t begin until project completion, a major goal for Theme 3 in Years 9-10 is to lay the foundation for this survey, to insure that a CfAO-led team carries out the most scientifically productive survey.

The single most important issue in such a survey is target selection. The infrared brightness of extrasolar planets decreases with age, as planets cool. Current imaging surveys for extrasolar planets have focused on the very youngest stars (<50 Myr), when planets may be quite bright ($f_{\text{star}}/f_{\text{planet}} \sim 10^5$). However, these young stars are necessarily rare and hence distant. GPI has been designed to observe planets at contrasts up to 10^7 . This allows more mature planets to be detected, but GPI still has greatest sensitivity for stars with ages below 1 billion years. Which stars fall in this “adolescent” category is actually poorly known – they are no longer clustered into easily-identifiable associations and lack the prominent features that make young stars stand out. CfAO researchers James Graham and Jason Wright are beginning a collaborative program to identify such stars, drawing on the existing target catalogs of Doppler planet surveys (which deliberately exclude young stars) and collaborating with astronomers in Canada, Australia, and the UK on a spectroscopic survey of the solar neighborhood to produce the definitive GPI target list.

Wavefront Sensing and Reconstruction

CfAO-funded research at LLNL has continued to make excellent progress on efficient and optimal algorithms for wavefront control. Poyneer, Marois and Macintosh developed analytic (based on previous work by Guyon and Ellerbroek) and numerical simulations of fundamental error terms in high-contrast AO including chromatic limitations due to carrying out wavefront

sensing in the visible while science images are generated in the IR. Figure 3.11 shows such an analytic calculation. Numerical wave-optics models were used to evaluate similar chromatic effects inside the GPI instrument itself (Marois et al 2006)⁵.

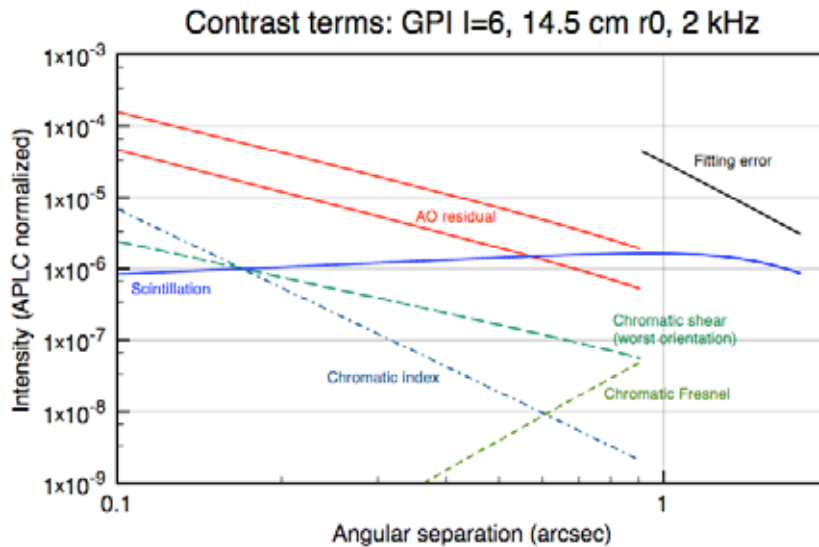


Figure 3.11: PSF intensity vs radius from analytic calculations of wave front phase and amplitude errors. “AO residual” shows the combined WFS measurement noise and temporal noise in the best and worst directions in the PSF. “Fitting error” is the classic atmospheric fitting term. “Scintillation” is normal intensity-fluctuation scintillation. “Chromatic shear” represents the different light paths between the visible WFS and IR science instrument at 30 degree Zenith angle. “Chromatic index” represents the path-length change due to dispersion of air.

ExAO systems with large numbers of actuators operating at high frame rates require wavefront reconstructors that are computationally efficient, accurate, and make the best use of the available photons. The CfAO LLNL group previously developed an efficient Fourier-domain reconstructor and then (in collaboration with Jean-Pierre Veran at HIA) extended it into an optimized modal-type framework, the Optimized Fourier Controller (OFC, Poyneer and Veran 2005) The next extension of this is a wavefront controller that predicts the motion of the atmosphere across the telescope. Several algorithms have previously been proposed for this (Gavel and Wiberg 2002, Dessenne et al 1998, Le Roux et al 2004), but these are generally computationally infeasible, capable of correcting only a single moving layer, and/or require a priori knowledge of the wind direction and speed.

The new predictive Fourier controller (Poyneer et al 2007)⁶ exploits the properties of the Fourier modes. First, the time evolution of a single Fourier mode under linear wind motion is easily expressed as a multiplication by a complex number. If we consider the temporal power spectrum of a single mode, it will be dominated by a narrow peak at a frequency set by the wind speed and modal orientation. Since Fourier modes are linear, in the case of multiple layers the power spectrum simply has multiple narrow peaks. This means that atmospheric layers can be identified directly in the telemetry of the AO system, and also makes it simple to derive a controller that preferentially rejects these narrow spikes, effectively deriving the wavefront 1 timestep in the

⁵ See Publications section – Publication #53

⁶ See Publications section – Publication#65

future from the past history. Figure 3.12 shows the potential improvement from this controller – the equivalent of one magnitude in star brightness

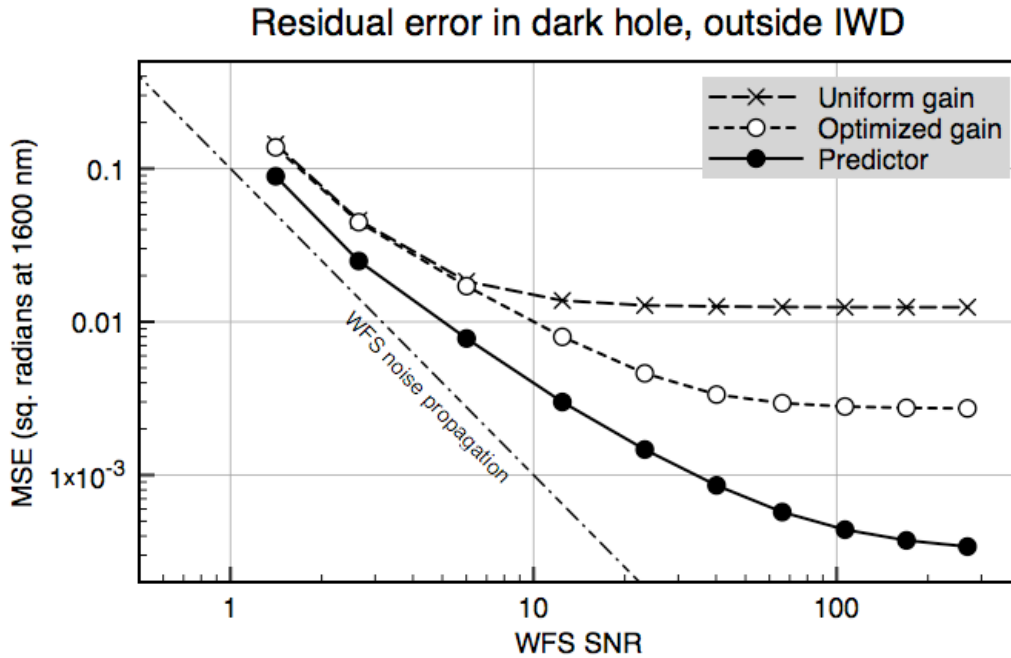


Figure 3.12: Wave front variance at controllable spatial frequencies vs WFS SNR for a plain controller, the baseline OFC controller, and the predictive controller. Dots correspond to $I=0$ to $I=9$ mag.

The LLNL group is now working to refine and verify this, using telemetry from existing AO systems or atmosphere-characterization experiments to establish the existence of multiple frozen-flow layers, and developing a practical implementation of the controller. Much of this work will be carried out using the Palomar AO system “Well-Corrected-Subaperture” (WCS). This is a modification to the existing PALAO system that remaps the 349-actuator DM to a 1.5-m subset of the 5-m primary mirror, producing effectively an unobscured 1.5-m telescope with an AO Strehl ratio greater than 90% (Figure 3.13). This architecture is well-matched to testing ExAO concepts such as spatially filtered wavefront sensing, predictive control, etc.

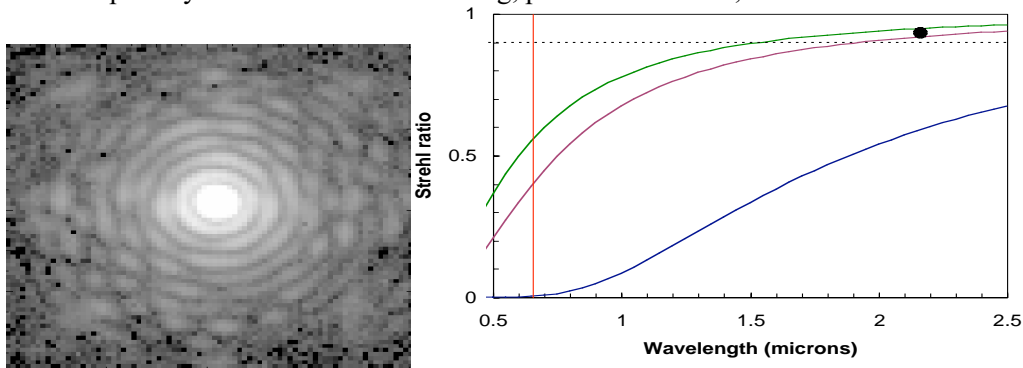


Figure 3.13 (Left) Image of the single star HD121107 obtained with a well-corrected 1.5 m off-axis subaperture on the Palomar Hale telescope. The passband is defined by the 1%-wide Br γ filter centered at 2.16 μm . This image is the sum of 20 short-exposure individual images, with a total integration time of 28 s.

Precision wavefront calibration

The single greatest factor limiting high-contrast observations with current AO systems is quasi-static wavefront errors from sources such as non-common-path calibration errors in the wavefront sensor. A key requirement for future AO systems is to reduce these static errors by 1-2 orders of magnitude. To do this, we must sense these wavefront errors at the science wavelength and as close as possible to the science instrument or coronagraph. In an ExAO architecture, the conventional Shack- Hartmann sensor cannot see these errors – it must operate at visible wavelengths to achieve high frame rates, has internal optics such as lenslets that introduce non-common-path errors, and will likely have undersampled pixels/quad cells and hence a limited linear range. To address this problem, the CfAO has developed an ExAO architecture incorporating a precision infrared wavefront sensor. This system is tightly integrated with the coronagraph and operates at the near-IR science wavelengths. Rather than attempting to control atmospheric wavefront errors, it measures the time-averaged wavefront to sense any systematic offset in the science wavefront. This time-averaged information can then be fed back to the main AO system to change the calibration of the Shack-Hartmann sensor, and/or be used to reconstruct the final PSF.

In Year 8, a team led by Kent Wallace at JPL has been working on the precision wavefront control that will be needed for future ExAO systems, such as the Gemini Planet Imager. With CfAO funding, the group has assembled a testbed implementation of this calibration interferometer (Figure 3.14) and demonstrated the ability to measure and control phase at the 1 nm RMS level (Figure 3.15).

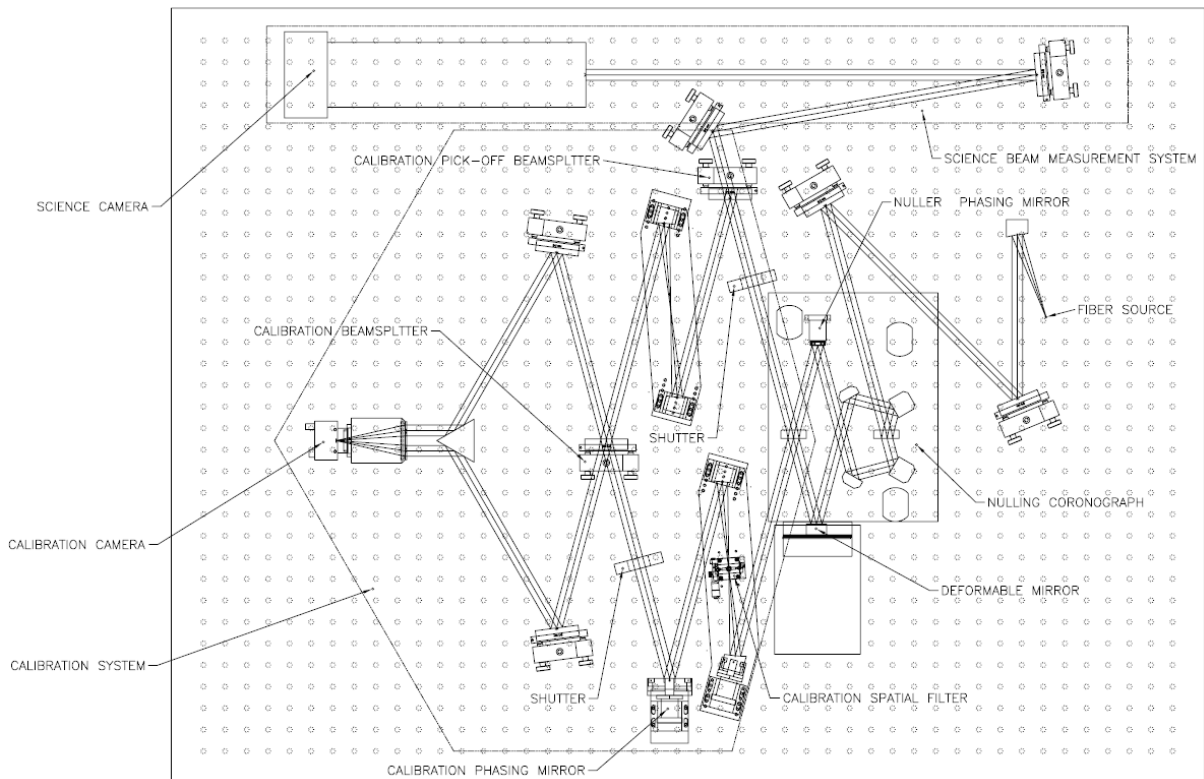


Figure 3.14: Layout of the JPL precision calibration testbed.

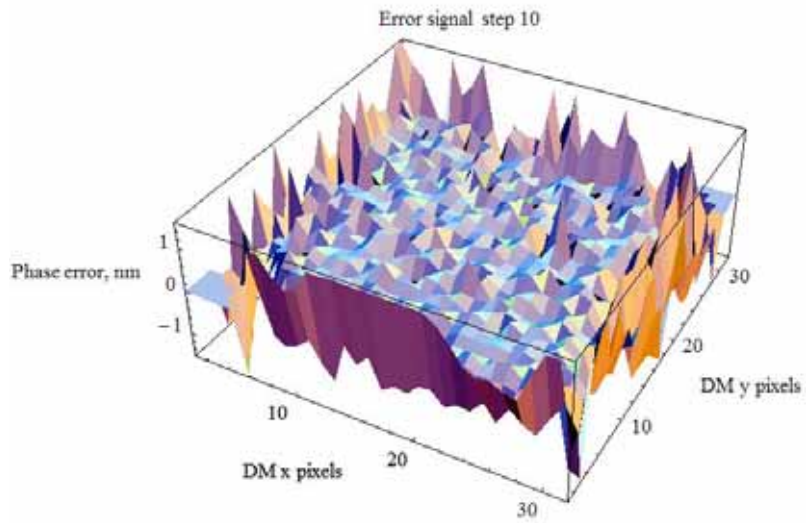


Figure 3.15: Residual phase errors as a function of DM element. The phase measurement was taken with broadband white light. (Both nuller and calibration interferometer were phased to work at the white light fringe.)

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

Introduction:

Scientific research using ophthalmic AO systems was demonstrated in the laboratory in Years 1-5. Scientists and engineers participating in the Vision Theme focused their efforts on the development of ophthalmic instrumentation equipped with AO, with the ultimate goal of commercialization. Initially a goal of this theme has been to extend the use of these instruments from the laboratory to clinics by engineering low cost, compact robust AO systems that can be used by clinicians who are unskilled in adaptive optics. In doing so, the newly developed and currently existing AO systems have also been used to advance our understanding of human vision, and to explore the medical applications of adaptive optics, thus providing the necessary feedback to developers, to assure the utility of the advanced AO instrument designs.

The goals for Theme 4 over the remaining two years are:

- Improve technology to image the retina in vivo at the 3-D resolution limit, exploiting confocal methods, OCT, fluorescence, polarization, retinal tracking, and post-processing in addition to adaptive optics.
- Improve and commercialize AO systems for correcting vision, such as AO phoropters that are superior to and replace conventional subjective refraction, and the use of such systems to clarify the role of optical and neural factors in visual performance.
- Expand the capabilities of adaptive optics instrumentation for vision science, such as improving wavefront sensing, deformable mirrors, control algorithms, or system calibration.
- Disseminate knowledge about vision AO by increasing connections with science, medicine and/or industry. Demonstrate possibilities for fundable research beyond Year 10.

Year 8 Results

Functional Imaging: Intrinsic Retinal Signals

Efforts to expand the capabilities of AO instrumentation have focused on relating function and structure in the retina. Two CFAO funded groups at Indiana and Berkeley have been exploring intrinsic retinal signals. In general, intrinsic signals refer to observable changes in the retina that occur in response to visible light stimulation. The two labs employ very different techniques and both labs made significant progress in Year 8.

Intrinsic Signal Imaging at Berkeley using AOSLO

Kate Grieve, a postdoc in Roorda's lab at UC Berkeley is leading the investigation of intrinsic retinal signals at high resolution using an adaptive optics scanning laser ophthalmoscope (AOSLO). The AOSLO employed its dual-channel capabilities (reported in the Year 7 annual report) to stimulate the retina with 658 nm visible light and simultaneously image the retina with 840 nm infrared light. Modulation of each laser beam using acousto-optic modulators (AOM) allowed integration of complex, patterned stimuli into the projected raster, whose exact locations on the retina were recorded into the movie in real-time. 20-30 second movies were recorded with stimulation occurring at 5 seconds. Intensity changes in the infrared image in response to the visible stimulus were monitored over time. In five observers, results showed a clear increase in infrared light scattering in the stimulated region with respect to its surroundings, reproduced in four observers across multiple imaging sessions. Signal increase began immediately at onset of

the stimulus, reaching a peak 2-3 seconds after stimulus onset, and decreasing to baseline within 2-10 seconds (see Figure 4.1). The magnitude of the increase over the stimulated area varied from 0 % to 5 % between subjects.

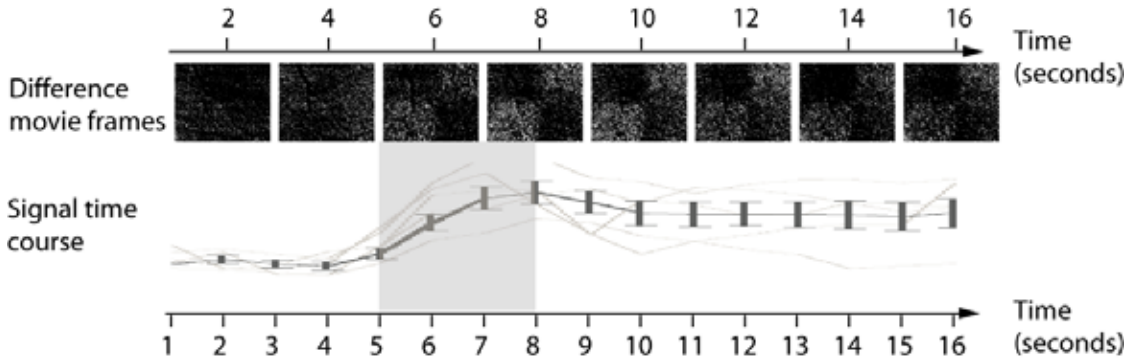


Fig. 4.1: Frames of a difference movie and time course of intrinsic signal, where the stimulus was a 2×2 checkerboard. The upper right and the lower left quadrants were exposed to a flickering red stimulus for 3 seconds. The images show the difference between each current frame and an average frame taken prior to stimulation. Each difference movie image comprises 30 averaged frames, corresponding to one second of imaging. Images at 2, 4, 6, 8, 10, 12, 14, 16 seconds are shown, and the corresponding signal time course is shown below. Error bars are \pm standard error of the mean. The solid gray curve is the mean of five trials; individual trial curves are shown in light gray.

The changes in the scattered intensity come primarily from the cones in the image, although not all cones contribute to the same extent. In individual cones which are represented on Figure 4.2 by the brightest regions of the image, signal increases over 20% were measured.

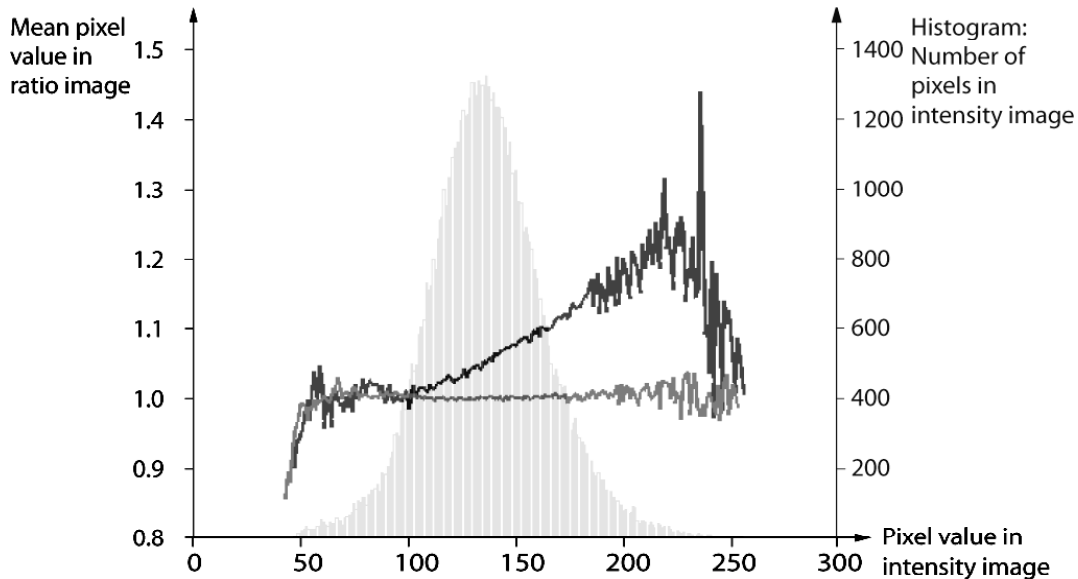


Fig. 4.2: Pixel by pixel correlation plots and image histogram, for a single trial from a single subject. Pixel values of the prestimulated intensity image are plotted against corresponding pixel values in a ratio image (i.e. a later frame divided by a pre-stimulus frame). Light gray line: frame 2 divided by frame 1 (both pre-stimulus), where no significant change in intensity is seen; dark gray line: frame 8 divided by frame 1 (post-stimulus divided by pre-stimulus), where an increase in intensity is seen across all pixel values, with the largest increase in the ratio image corresponding to the brightest features in the intensity image, which correspond to cone centers. These curves are plotted from a movie in which frames were averaged in groups of 30, corresponding to one second intervals. The background plot is a histogram showing the distribution of pixel values in the pre-stimulated intensity image.

Intrinsic Signal Imaging at Indiana: Interference-based methods

Experiments conducted in Year 7 by Yan Zhang, Jungtae Rha and Ravi Jonnal, members of Don Miller's lab, had demonstrated that the scintillation phenomenon is due to interference between reflections from various layers in the retina, and also that scintillation is only observed when the cones are stimulated with visible light. OCT measurements taken at Indiana on the same subjects suggest that the interference leading to scintillation is between bright reflections at the anterior and posterior edges of the cone's outer segment. Nevertheless, the physiological source of scintillation, presumed to be the bleaching of cone photopigment, had not been established. Most experiments conducted in Year 7 had utilized a single visible source (670 nm laser diode) both for imaging and stimulating the cones.

To investigate the physiological source of scintillation, they modified the camera so as to have separate imaging and stimulus sources, imaging with a relatively invisible infrared source and stimulating with the red laser diode. The separate sources allowed measurement of functional behavior of cones in the infrared, and better control of the retinal illuminance in the stimulus. Preliminary data were collected using the 915 nm laser diode and Sarnoff camera, which operates at 192 frames per second (see Figure 4.3). The new apparatus allowed substantially better measurements of scintillation behavior and led to several key observations:

- A. Scintillation is not necessarily dependent upon optical changes in the photoreceptor due directly to photopigment isomerization, or bleaching, as was previously surmised.
- B. The RMS, over time, of an individual pixel in a registered video indicates the amount that pixel varied in intensity over time. An image built up of these RMS values gives a qualitative picture of the amount of scintillation in the cones.
- C. Scintillation provides a direct measurement of the temporal characteristics of underlying physiological processes. Initial results suggest that the duration of the scintillation is approximately 400 to 500 ms, and that the onset of scintillation occurs within the first 5 – 10 ms following stimulation.
- D. While the RMS and duration of scintillation appear to be independent of stimulus level, the frequency of scintillation appears to be dependent upon it (see Figure 4.4).

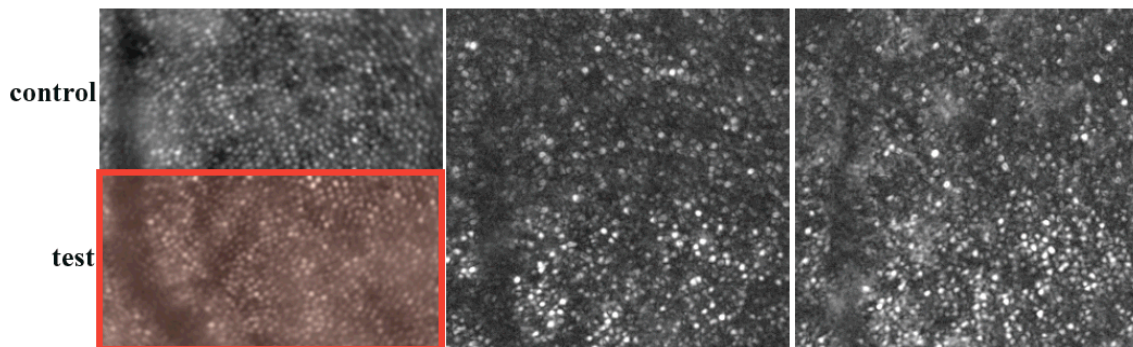


Figure 4.3. (left) Imaged region of cone mosaic in one subject shown with superimposed (red) indicator of stimulated subregion. (center and right) RMS images of the same patch of cones is shown after the subregion is stimulated with $5 \times 10^5 \text{Td s}$ and $8 \times 10^6 \text{Td s}$, respectively. Note the qualitative similarity of stimulated regions, in spite of a 16-fold increase in retinal illuminance.

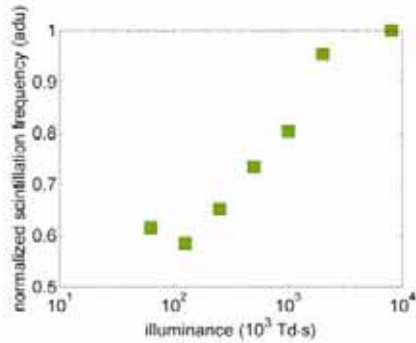


Figure 4.4. Plot of the frequency of scintillation versus the retinal illuminance of the stimulus. Data are averaged over 25 cones, chosen for their high visibility, with two measurements at each stimulus level except the brightest. There appears to be a strong dependency of scintillation frequency upon stimulus level, but a full statistical analysis has not yet been performed.

Miller’s group is only just beginning to discover the various physiological processes, optical phenomena, and independent experimental parameters that underlie the phenomenon of cone scintillation, and the scope of experiments that are being planning is large and varied.

Visual Psychophysics with Adaptive Optics

Eye tracking applications of AOSLO at Houston and Berkeley

The natural jitter of the human eye during fixation shows up in AOSLO videos as image deformations. Using custom-written analysis tools, Girish Kumar and his supervisor Scott Stevenson at the University of Houston have extracted eye movement data from AOSLO videos recorded at Roorda’s lab at Berkeley during a variety of fixating and tracking tasks. The sensitivity of this system is unprecedented in comparison to other methods of eye tracking and they have extended measurements of fixation eye movements down into the arc second range. They have also developed tasks to identify those points in the fovea used by the eye movement control system as targets for “looking at” an image feature.

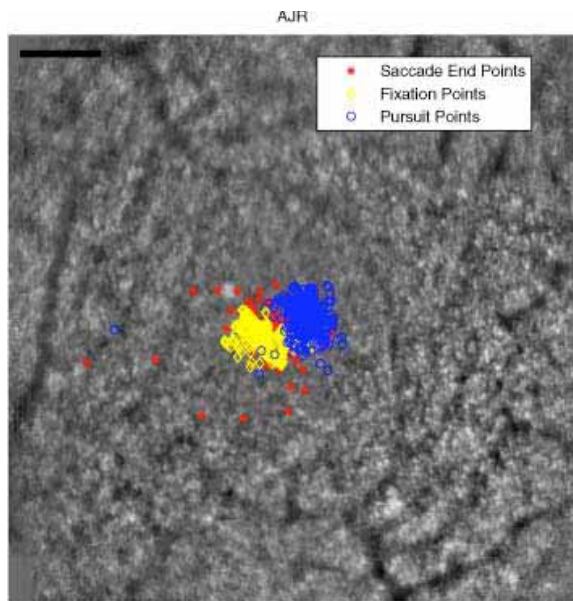


Figure 4.5. Superimposed on this retinal image from AOSLO are image landing points in central fovea for three different kinds of eye movement. Yellow points indicate where an image falls when a subject fixates it steadily, blue points show where an image falls when a subject pursues a moving image, and red points show where an image lands when a subject makes a quick movement to a peripherally seen image. The landing regions are distinct for the three tasks in some subjects, indicating some independence in the targeting control.

These and prior AO-based results are redefining our understanding of the fovea. We have already learned (based on research of Nicole Putnam while she was an undergraduate researcher in David Williams’ lab at the University of Rochester) that the preferred fixation location does not necessarily coincide with the position of maximum cone density in the retina. These new results

indicate that the fovea is not only offset from the anatomical fovea, but that its position is also task dependent.

Optical and Retinal Limits to Human Vision at UC Berkeley

Ethan Rossi, a graduate student working in Roorda’s lab at UC Berkeley, undertook a carefully controlled study comparing adaptive optics corrected visual acuity in 9 emmetropes and 10 low myopes. They found that emmetropes and low myopes will both benefit from AO correction in a visual acuity task, but not to the same extent. Low myopes were found to perform worse than emmetropes in a visual acuity task after AO correction in both angular (minimum angle of resolution) and retinal (critical feature size) units (Figure 4.6). In addition, they found that residual optical aberrations do not limit visual acuity in low myopia after AO correction and that there is no difference in the high order aberrations of emmetropes and low myopes. Retinal and/or cortical factors were determined to limit visual acuity after adaptive optics correction in low myopia.

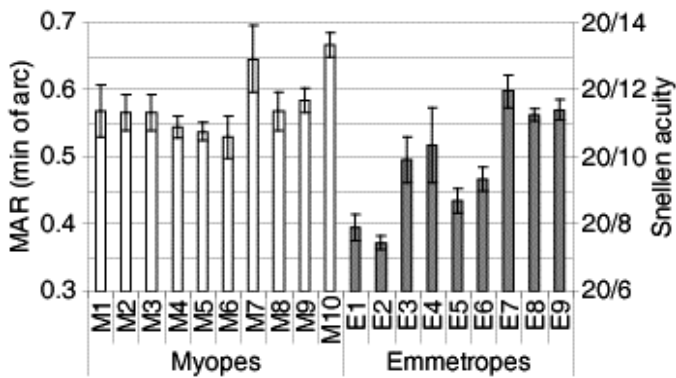


Figure 4.6. Spectacle magnification adjusted AO-corrected MAR. Error bars are +/- SEM. Spectacle magnification slightly reduces the difference between groups.

Rossi is currently studying the relationship between the photoreceptor spacing in the parafovea (where the cones are visible) and visual acuity. He has measured the cone spacing in four eyes at ~1, 1.5, 2 and 2.5 degrees from the preferred fixation locus and performed psychophysical measures of visual acuity in these areas. There was a strong correlation between the photoreceptor row spacing (as measured from FFTs of the photoreceptor mosaic) and visual acuity out to about 1.5 degrees. Beyond this point, there was a divergence between visual acuity as measured with a tumbling E task and photoreceptor spacing. Specifically, subjects performed worse than would be expected based upon sampling theory (See Figure 4.7) The plan is to continue research into this finding by exploring further how different measures of acuity relate to cone spacing in the parafovea, using a two point resolution task, as well as sinusoidal gratings.

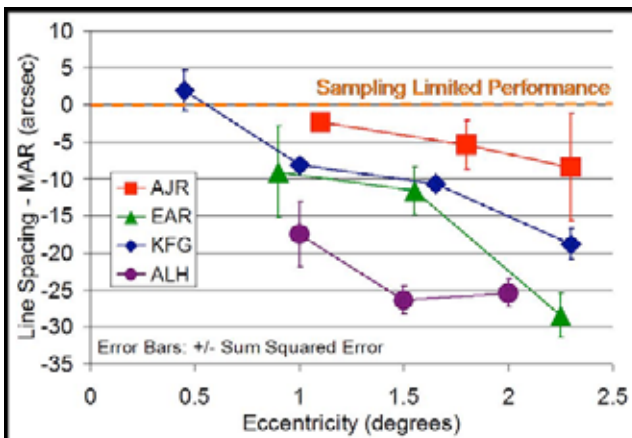


Figure 4.7: Difference in line spacing and minimum angle of resolution as a function of eccentricity. If the limits to vision were due entirely to photoreceptor sampling, then the points would have fallen along a horizontal line. The line slope is negative, indicating that for this task, additional factors limit visual performance.

Improved Registration of AO SD-OCT images at Indiana

Several imaging processing tools were targeted for development or improvement in Year 8 based on anticipated usage of the two retina cameras. These include axial registration of A-scans, background correction, and investigation of dewarping of volume images. Progress on each is described below. Vision science projects with the AO SD-OCT camera sometimes require accurate alignment of adjacent points on an OCT retinal cross-section image (also called a B-scan). Such alignment is typically absent because of inherent axial motion of the eye during the acquisition. In Year 8 Indiana compared several different approaches for axially registering B-scans with particular emphasis on registering relative to the inner limiting membrane as they were interested in studying the nerve fiber layer. Figure 4.8 illustrates the improvement provided by oversampling of B-scans at 3 and 6 degree eccentricity. The left column shows B-scans registered with cross-correlation alone; the right shows registered B-scans with four times over sampling, which corresponds to sub-micron sampling of the retina. Note the improved registration with over sampling.

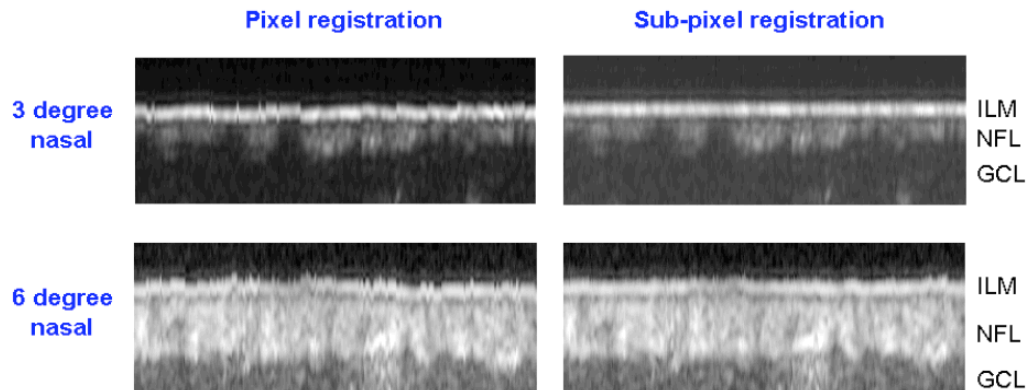


Figure 4.8. B-scans acquired with AO-OCT and post-processed to correct for axial registration errors. The right column illustrates the additional improvement provided by over sampling by four times prior to registration.

Stabilized Stimulus Delivery - Montana State University and UC Berkeley

Early in Year 8, Qiang Yang, a postdoc working with David Arathorn and Curt Vogel at MSU, completed the software for real-time correction for image distortions in the adaptive optics scanning laser ophthalmoscope (AOSLO). Stabilization was excellent, correcting each frame with an intraframe accuracy of about 6 arcseconds, or a fraction of a single foveal cone.

MSU worked closely with members of the UC Berkeley group to use the real-time retinal image motion signals in combination with high speed modulation of a scanning laser to project stabilized, aberration-corrected stimuli directly onto the retina. In three subjects with good fixation stability, the delivered stimulus location error had a standard deviation of 0.26 arcminutes or approximately 1.3 microns, which is smaller than the cone-to-cone spacing at the fovea (see Table 1). This performance is equivalent to or better than any other technique with the important advantage that the exact location of the stimulus is unambiguous and the stimulus can be delivered with ultra-sharp clarity through the AO-system. For the first time, it is possible to

target a single cone in the retina and stimulate only that cone with visible light. Potential applications include targeted microperimetry (functional vision testing) and possibly microsurgery.

Table 1: Stimulus stability records based on a total of 13 video sequences from three subjects.

	horizontal stimulus error (SD in arcminutes)	vertical stimulus error (SD in arcminutes)
Subject A (6 videos)	0.20	0.24
Subject B (4 videos)	0.25	0.32
Subject C (3 videos)	0.28	0.27

Improvements in Contrast and Resolution

Rochester - Image Primate Ganglion Cells Using the Fluorescence Adaptive Optics Scanning Laser Ophthalmoscope.

Fluorescence imaging with the use of dyes or natural fluorophores is a means of providing contrast to transparent retinal cells that has rarely been applied to *in vivo* high resolution retinal imaging. Rochester has developed methods following those described by Dacey et al. (2003) to label retinal ganglion cells by injecting fluorescent dyes in the lateral geniculate nucleus (LGN) of monkey brains. By labeling cells in a monkey retina, they hope to image them at high resolution, and characterize them by resolving their dendrites.

Such photodynamic ganglion cell labeling with rhodamine dextran dye enabled the first *in vivo* resolution of sub-cellular features of ganglion cells in a monkey. The benefit of adaptive optics for fluorescence imaging was demonstrated by an increase in resolution, intensity, and image contrast. Experimentation was done on two monkeys, demonstrating routine visualization of dendrites and axons. Analysis of the same tissue on a confocal microscope showed that the *in vivo* imaging revealed much of the fine axon and dendritic detail (Figure 4.9). This result shows that is possible to distinguish retinal ganglion cell types and observe their fine processes in the normal and diseased retina *in vivo*. These results represent dramatic progress since CFAO Year 7, where only the large cell bodies of ganglion cells could be clearly seen.

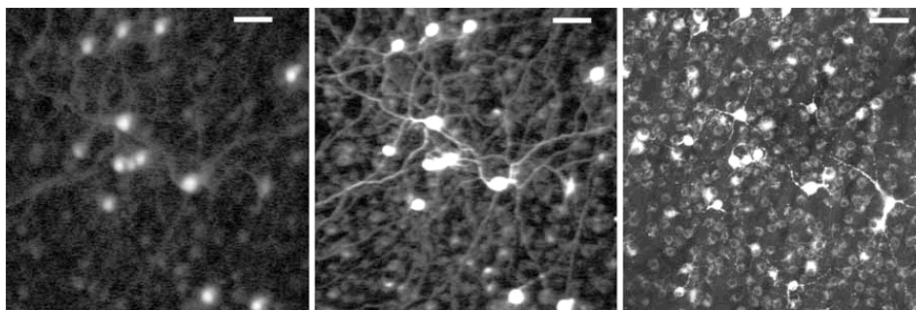


Figure 4.9: Left: *In vivo* image without AO. Center: *In vivo* image with AO. Right: Corresponding *ex vivo* image using a 0.7 NA microscope objective. Scale bars are 50µm.

Targeted light delivery to individual ganglion cells was briefly explored for investigation of ganglion cell function. The results showed that ganglion cells, underlying photoreceptors, and RPE cells were damaged as a result of excess light exposure and not from phototoxicity of rhodamine dye. This was a clear sign that alternative methods should be explored such as GFP

labeling and development of selective “switches” to inactivate particular ganglion cell types genetically.

Efforts to Exceed the Diffraction Limit using Structured Illumination

Sapna Shroff, a PhD student at the University of Rochester is implementing structured illumination on a flood-illuminated adaptive-optics retinal imaging system to enhance its lateral resolution beyond the diffraction limit set by the dilated pupil of the eye. *In vivo* imaging of the human retina illuminated by a sinusoidal fringe patterned illumination has been successfully implemented. A scanning system has been incorporated to reduce speckle in the images. These fringe-illuminated images have been registered with respect to a uniform illumination flashlamp image. Ideally, images of the object are taken with the fringe illumination shifted by small known amounts in each image. However, the *in vivo* retina moves by itself in an unpredictable way. Therefore, it is not possible to have any prior knowledge of the resultant phase-shifts of the sinusoidal illumination in each image of the moving retina. Shroff has developed an algorithm to estimate these random phase-shifts without any prior knowledge.

The phase-shift estimates appear to be fairly accurate, and they have been used in simulated reconstructions to see how effective they can be for recovery of high frequency information in the image. The results are shown in Figures 4.10. Reconstructed images show no fringe artifacts resulting from inaccuracies in phase-shift estimates.



Figure 4.10: Left frame: Conventional image taken with uniform illumination. Center frame: Reconstructed composite with $f_o = 0.5 f_c$, SNR of 100, using estimates of the phase shift. Right frame: Reconstructed image with $f_o = 0.91 f_c$, no noise, using estimates of the phase shift.

Current literature on structured illumination algorithms requires imaging of incoherent fluorescent objects. Most cells in the human retina do not have significant fluorescence properties. Therefore there are both complete and partial coherence conditions in the retinal images. Shroff has developed a theory for the analysis of such images and is also developing an algorithm to reconstruct such coherent or partially coherent images. This will enable the application of structured illumination imaging to any non-fluorescent object.

Collaborative Efforts

The collaborative efforts of Theme 4 members go well beyond the members of the CFAO. Most groups are extensively involved in collaborations, and have used CfAO to leverage significant additional funds for basic science, clinical and engineering efforts. These collaborations are serving to disseminate AO to the vision science and medical communities. The following sections highlight some new examples.

Academic Collaborations:

Combined Stabilized Stimulus Delivery and Electrophysiology (MSU, Berkeley and UC San Francisco)

The tracking capability works best on eyes with good fixation. This year, Berkeley and MSU have started collaborating with Jonathon Horton's group, specifically Lawrence Sincich, at UC San Francisco to deliver retinally-stabilized stimuli to the retina of a macaque simultaneously with electrophysiological recording. The goal is to directly measure the signals that individual cones generate at the level of the ganglion cells, whose axons form the optic nerve exiting the eye and whose signals can be recorded with electrodes placed in the lateral geniculate nucleus. The AO correction allows us to stimulate single cells and the stabilized stimulus delivery allows us to maintain that stimulation light on any specified cone, despite constant eye movements. This research synthesizes most of UC Berkeley's and MSU's technical efforts and represents an innovative and potentially fruitful application for adaptive optics.

Models to Predict Percepts of Microstimulated of Single Cone Photoreceptors

Heidi Hofer and Osamu Masuda, using the Adaptive Optics Ophthalmoscope in David Williams' lab, have completed new experiments to study the microcircuitry underlying human color vision using small light flashes delivered to single cones with adaptive optics. They have now shown that the color appearance of single spots does depend, in a statistically significant way, on the mosaic location that is stimulated. David Brainard at the University of Pennsylvania has developed a Bayesian model of these results that is able to predict reasonably well subject's reports of color appearance. This model incorporates the subject's optics and cone mosaic and a learning rule in which local color circuits are formed so as to maximize the probability of correctly estimating the color appearance of objects seen through the natural optics.

Collaborations with Industry

Indiana & Thorlabs

The project was a feasibility study of new swept source technology for AO-OCT and involved integration of a Thorlabs' prototype 850 nm swept source into the established Indiana AO-OCT camera. While spectral-domain OCT has commanded the most recent attention owing to its substantially higher acquisition speed without loss in sensitivity, other less developed OCT architectures, in particular swept source OCT, may offer additional benefits that are attractive for retinal imaging. Thorlabs' offer to visit Indiana with their prototype 850 nm swept source seemed appealing as it required only personnel time to perform the evaluation and provided us firsthand experience of this new technology.

Figure 4.11 shows a layout of the AO swept-source OCT camera. The light source and detection channels were provided by Thorlabs. Volume and B-scan images up to 1° in diameter were acquired at retinal eccentricities of 2° and 7° on two subjects with focus ranging from the nerve fiber layer to the photoreceptors.

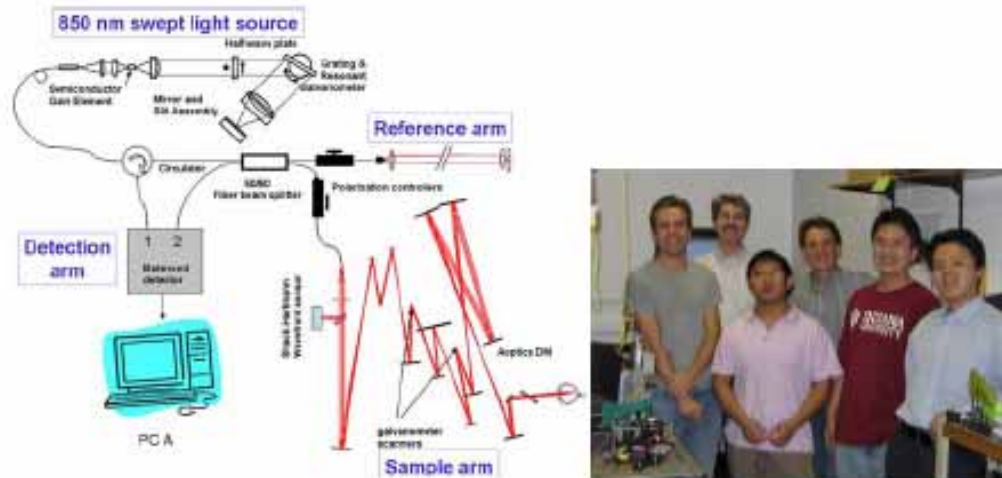


Figure 4.11. (left) Layout of the AO swept source OCT camera that was evaluated by (right) the Thorlabs and Indiana groups. President and founder of Thorlabs, Alex Cable, is shown in the back row, center.

Figure 4.12 shows B-scans acquired with the AO swept source OCT at 2° eccentricity for one subject. Focus was systematically adjusted (0 to 0.6 diopters) using the AOptix wavefront corrector. Brightness of the neural layers was highly sensitive to the placement of focus, which is consistent with previous reports in the literature. Good agreement was found between the thickness of the retina and the dioptric shift required to maximize reflections from the photoreceptors and nerve fiber layer. Quality of the B-scans approaches that reported with AO SD-OCT.

Further, C-scans (Fig. 4.12) extracted from volume images at 2° and 7° revealed individual cone photoreceptors, again approaching the quality of images collected with AO SD-OCT. However, as is evident from Fig. 4.12 (a-d), reflections from the outer segment tips were more difficult to distinguish from neighboring layers owing to the reduced resolution of the swept source, and motion artifacts were more apparent due to the slower speed (20 KHz compared to 75 KHz). Small blood vessels were readily apparent at both eccentricities.

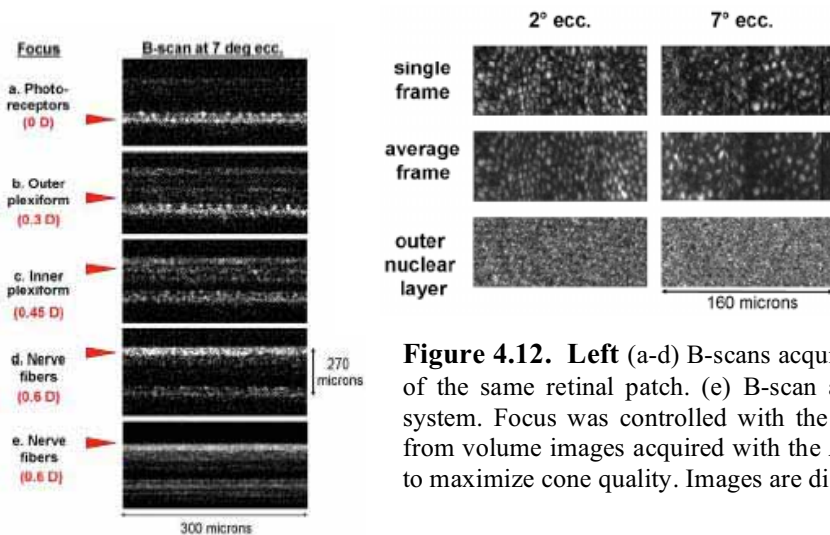


Figure 4.12. Left (a-d) B-scans acquired with the AO swept source OCT camera of the same retinal patch. (e) B-scan at same patch with 30 KHz AO SD-OCT system. Focus was controlled with the AOptix mirror. Right: C-scans extracted from volume images acquired with the AO swept source OCT. Focus was adjusted to maximize cone quality. Images are displayed in linear amplitude.

Iris AO & Bausch and Lomb

The DM fabrication and open-loop control improvements have also ushered in tremendous system-level progress. Iris AO was able to finish a long-standing development contract with Bausch & Lomb (B&L) to incorporate its DM into a Zywave aberrometer. With careful design and custom made optical mounts, they were able to fit all of the optics into the existing footprint of the Zywave with the exception of the wavefront sensor camera. The Zywave cover had to be slightly modified to allow the WFS to be moved out a small amount.



Figure 4.13: AO-equipped Zywave aberrometer modified by Iris AO. Iris AO managed to add AO capabilities within the footprint of the *clinical* device.

Rochester, Berkeley & Optos

Based on a recent discussion in 2007, Optos, who licensed a series of patents from Williams and Roorda in 2006, appears to be making excellent progress toward the development of commercial AO ophthalmoscope. In addition to the development of a widely used commercial system, Optos has also decided to develop research-grade instruments which will be deployed in selected research labs.

Dan Gray, a recent PhD graduate from David Williams lab Rochester, has taken a job with Optos and we expect that this hire will accelerate progress as well as enhance our ability to transfer our latest technology and experience for their devices.

Clinical Collaborations:

AO Imaging of Inherited Retinal Disease

Members of Roorda's lab at UC Berkeley and Jacque Duncan, MD, at the Dept of Ophthalmology at UC San Francisco are continuing their study of patients with inherited retinal degenerations. So far they have detected significant difference in eyes with disease compared to normal. Structural measures from AO images have been shown to correlate with standard clinical measures. A summary of the microscopic imaging results on patients with several disorders has been recently reported. They also reported, for the first time, direct imaging of retinal pigment epithelium cells in human eyes. The images do not require any extrinsic or intrinsic fluorescent agents, but they are finding that the visibility of the RPE mosaic indicates that significant loss of photoreceptors has taken place.

AOSLO imaging is also being used to image patients who are undergoing phase II clinical trials of the Neurotech (www.neurotechusa.com) ciliary neurotrophic factor (CNTF) implants. These implants are designed to continuously deliver a small dose of neuroprotection factors to slow the

progression of blinding diseases, like retinitis pigmentosa. UCSF is one of only a few sites in the country where the Phase II trials are taking place.

The primary goal of this collaboration is to better understand inherited retinal degenerations and to demonstrate AOSLO as the best tool for noninvasive monitoring of therapies for these degenerations.

Development of MEMS Mirrors for Vision Science

Iris AO

Drive Electronics Progress

As part of a sale to Steward Observatory, Iris AO has built an interface board to run a BMC mirror with the SmartDriver electronics. The precision calibrated SmartDriver electronics replaced the low-resolution 8-bit electronics Boston Micromachines Corporation (BMC) provides for its DMs. In response to questions of how the electronics were working, Dr. Codona responded, “The dual driver system is working nicely and I have now got it driving the two segmented DMs in the lab as the two halves of an interferometric complex field modulator. I couldn't be happier with how things are working!” Iris AO is currently developing its 2nd-generation compact drive electronics under a Phase II SBIR with NASA. The second generation electronics will provide even better performance and are much more compact. The second generation electronics and flex-circuit interface are shown in Figure 4.14



Figure 4.14: Second generation drive electronics with and flex-circuit mirror interface board (upper small box and narrow flex cable) atop the first generation electronics and mirror interface board. Second generation electronics with USB computer interface will be available July 2007.

AO Controller Progress

A big challenge for Iris AO has been to demonstrate that it is possible to use a segmented DM with a Shack-Hartmann wavefront sensor (SHWFS). To address this, Iris AO has developed a Zernike-based controller that is optimized to our segmented DM. A key aspect of the controller is a precision open-loop control of the DM segments. With excellent open loop segment positioning combined with an AO controller that sends position commands that approximate a continuous surface, they have successfully demonstrated the controller on a test bench. This controller has also been bench marked on a low cost DSP chip to operate at faster than 30 Hz.

Testing on a Human Eye

Most significant progress at Iris AO has been the demonstration of cellular-level retinal imaging using an Iris AO DM. Iris AO tested its DM in the flood-illuminated AO retinal imaging system at the UC Davis Medical Center. Prof. Jack Werner allowed Iris AO to test its DM in the system at Davis and Steve Jones of LLNL helped with extracting wavefront sensor data. The images in

Figure 4.15 show the DM placed in the system at UC Davis and the two images to the right are of the retina with the DM flattened and with the DM correcting a measured aberration profile. The image is not of the quality that many now see because the AO correction was run open loop. Because of limited time, the AO control was integrated via “sneaker net.” In other words, the existing wavefront data from the UC Davis wavefront sensor were loaded onto a USB memory stick and manually transferred to the separate control computer that ran the Iris AO DM. Despite the open-loop nature of the correction, they were still able to image photoreceptor cells that could not be imaged without AO (e.g. with the Iris AO DM flattened).



Figure 4.15: (Left) Photograph of the Iris AO DM placement in the AO flood illuminated fundus camera at UC Davis. (Center and Right) “AO off” and “AO on” retinal images using the Iris AO DM in the UC Davis system. Images were taken using a single-iteration open-loop correction. Wavefront data were transferred between computers via USB memory stick, PTT DM segment positions were calculated and sent to the DM for correction. Time between wavefront sensing, correction, and image acquisition was approximately 2 minutes.

Through the work at UC Davis and also through the Bausch & Lomb project Iris AO has demonstrated the open loop functionality of the Iris AO DM. This next task will be to extend this work using the new Iris AO DM controller to run the Iris AO DM in a full closed loop AO mode with a 30 Hz update rate on a human subject. This work will be performed in Roorda’s lab at UC Berkeley.

Boston Micromachines Corp

Early generation BMC mirrors are being used in almost every MEMS-based vision science AO system and have demonstrated excellent performance, albeit with limited stroke. BMC’s Year 7 goal to produce 6-micron stroke mirrors was completed and they are currently delivering the 6-micron stroke mirror to a series of vision science labs. BMC’s Year 8 goal is to develop MEMS actuator arrays with even more stroke (8 μ m). The recent processing advance allowing large-gap (16 μ m) electrostatic actuators is being combined with stroke-extending architectures developed by BMC, including modification of actuator geometries and layer thickness,

Table 2: Expected actuator characteristics

Phase I Actuator Array Characteristics	
Number of actuators/array	140
Actuator pitch	550 μ m
Actuator stroke	$\geq 8\mu$ m
Maximum actuation voltage	100-250V
Aperture (140 element array)	6mm

Extensive design and modeling were performed in this effort, with focus on generation of optimized actuator and electrode geometry. Specialized MEMS modeling software (Abaqus and Coventorware®), capable of coupling electrostatic and mechanical analysis, was used in the modeling and design process. Iterative algorithms were also utilized to exploit each of the geometrical variations to arrive at optimized actuator designs.

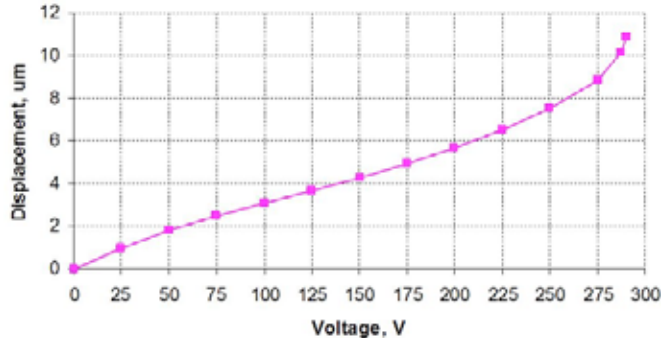


Figure 4.16. Electromechanical performance prediction for the proposed MEMS DM actuator using split-electrodes, actuator membrane perforations, extended span, and a 16µm actuator gap. Greater than 8µm of mechanical stroke can be achieved.

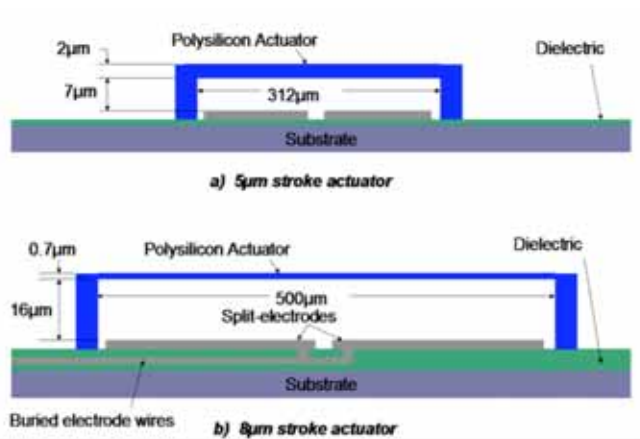


Figure 4.17. Comparison of heritage BMC MEMS actuator and new actuator design for 8µm of stroke.

The designs for these device have been laid out and sent to a commercial foundry for fabrication. Devices are expected back in Q3 of this year.

II.2b Research Management (Metrics)

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

In the spring of each year, researchers forward their proposals to the CfAO for continuing or new research. Proposals are reviewed by external and internal reviewers and then discussed in committee. Each internal proposal includes a set of Milestones. Performance relative to these milestones is a strong consideration in the decision for further funding. Those proposals "on the edge" are directed to the PAC for discussion and advice. Funding decisions are typically made by the end of June each year. The official annual cycle for funding begins on November 1.

The Center organizes annual Fall and Spring Retreats which are attended by most researchers, graduate students, and postdocs. This year's Spring Retreat (2006) differed from those of previous years in that it was held at UCSC as a series of sequential and overlapping Theme Workshops. The thematic approach enabled participants to have "in depth" sessions in their discipline and by overlapping some sessions and meal times the desired information exchange between disciplines was achieved. An example of this focused thematic approach was in Theme 4 where attendees were encouraged to demonstrate and exchange vision science software they had developed. Participants at these sessions considered them to be most informative and a success. In addition, smaller workshops and symposia on specialized topics are held during the year as the need arises.

Partnerships

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

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

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

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

II.2c. Research Plans for the coming year

Theme 2. Future Plans for AO with Extremely Large Telescopes

In Year 9 we will continue to support work towards the fruition of promising component technologies and breakthrough astronomical AO science.

The Galactic Center research work of Andrea Ghez (UCLA) continues next year as well as the CATS project led by Claire Max (UCSC) and the solar system work of Imke DePater (UCB). Frank Marchis has moved on to a position within the SETI Institute and submitted a winning proposal to continue his work imaging asteroid companions and trans-Neptunian objects. All of the funded astronomical science research is only made possible with adaptive optics on large telescopes.

On the MEMS front, the MEMS consortium funded in Year 7 has continued on on its own with funding from the Gemini Planet Imager project. This will be the first astronomical AO instrument to employ a MEMS deformable mirror, and is a milestone for which the CfAO can truly take credit. The two continuing MEMS technology projects funded for Year 9 are the development of metal-deposition technology MEMS at UC Santa Cruz and the development of through wafer interconnects for MEMS by Boston Micromachines.

Lasers always seem to be behind schedule with respect to promises and predictions. The CfAO's role here is to make the higher risk investment into advanced next generation technology that can potentially have a high payoff. We are coupling the LLNL laser work, we are coupling it with UCO/Lick's Villages experiments and promoting a new goal of getting this laser system to the telescope with on-sky tests in 2008. The fiber laser work is concentrating on the pulse and spectral format that will most efficiently excite the Sodium layer. It will also be chopped to allow for time-gating – an ideal format for astronomical AO. The CfAO is partnering with AODP to reach this common goal, but because of the slow progress has agreed to fund Year 9 only with significant ongoing oversight by the Theme 2 leader. At Palomar, the recent successful closed loop operation of the Chicago laser can be directly attributed to CfAO's insistence that the laser move to the observatory a few years ago. CfAO will not be supporting laser work at Palomar in Year 9.

CfAO sponsored two workshops last year specifically focused on guidestar laser technology. These are fostering collaboration and technical interchange that otherwise would not have been possible. We will continue to host these workshops on a bi-annual basis.

The Gemini South 8-meter telescope MCAO system is due to be commissioned in early 2008. Eddie Laag, of UC Riverside and student of Prof. Gabiella Canalizo, will be funded for time and travel expenses to participate in the Gemini MCAO commissioning work at Cerro Pachon, Chili. Eddie has been in close contact with Francois Rigaut who is the lead astronomer for the MCAO project and an active participant in CfAO activities. This activity highlights the collaborations fostered by the CfAO within the astronomical AO community.

Theme 3. Future Plans for Extreme AO

The cornerstone of the CfAO ExAO theme is the construction and deployment of an operational high-contrast AO system for the discovery of extrasolar planets. Our strategy in this Theme is to support fundamental research and development activities required to enable the deployment of an ExAO system on an 8-10 meter telescope, with construction funds provided by an external source. We have completed a detailed preliminary design for such an instrument, the Gemini Planet Imager, selected for funding by Gemini. Selection and full funding by Gemini was a major outcome for the CfAO ExAO effort.

First light for GPI, and the planned large-scale survey, will occur beyond the CfAO time horizon (2011-2014.) In Years 9 and 10, the CfAO will continue to support the basic research and development needed to enable and enhance this instrument. At LLNL, CfAO will fund development of advanced wavefront control algorithms suitable both for GPI and future ELT ExAO systems, especially the predictive control algorithm. At JPL, Kent Wallace will develop and prototype an advanced interferometric wavefront sensor.

A particularly crucial area for the CfAO to support is the science planning for GPI. At UC Berkeley, CfAO will fund GPI Project Scientist, James Graham, in development of the GPI science case and planning for GPI science operations. As discussed above, Gemini intends to carry out a 100-200 night GPI survey of nearby stars, with a team selected from competitive proposals. The most crucial issue in designing such a survey is target selection – identifying a large population of moderately young (100 – 2000 Myr) nearby (<50 pc) field stars. Other key issues include developing image processing techniques to extract planetary signals from point spread function speckle noise. By supporting the science planning for GPI now, we will insure that this CfAO legacy is used effectively when it becomes operational.

Gene Serabyn will construct a prototype ExAO system at Palomar, using a well-corrected 1.5 meter subaperture, to enable initial studies of ExAO images on the sky and verify ExAO concepts in high-Strehl ratio tests. At UCLA and UC Berkeley, Andrea Ghez and James Graham will use current AO systems for high contrast science. CfAO will provide coordination of the different institutions involved and connections to the broader astronomical community, and will organize workshops.

Theme 4 Future Plans for Vision Science AO

UC Berkeley

The first goal at Berkeley is to fully exploit the use of stabilized stimulus delivery for use in visual psychophysics and for advanced functional testing of the retina for clinical applications. Berkeley also plans to better understand the imaging limits in the AOSLO, particularly as it relates to imaging foveal cones, which have only been visualized in flood-illuminated imaging systems like the one at the University of Rochester. They will develop an optical model of the cones and with simulations, develop strategies by which these cones can be resolved in a scanning laser system. They will also work to optimize the performance of the MEMS mirrors to obtain the best possible resolution.

Year 9 Milestones

- Implement online eye-motion correction and video stabilization onto AOSLO instrument.
- Implement eye tracking and stimulus stabilization to improve intrinsic signal experiments
- Add sophisticated MEMS mirror control into AOSLOII system
- Measure how fixation stability depends on fixation target and task

- Determine how the photoreceptor mosaic and eye movements limit human vision.
- Develop an accurate model for interference and imaging limits in the AOSLO.

University of Rochester

The Rochester group is proposing to complete the two major CfAO-funded projects in the remaining two years of CfAO funding. In Year 9, they propose to make substantial progress on microstimulation experiments in which the color appearance of lights that stimulate single cones is recorded, and on a project to use structured illumination to surpass the diffraction limit in images of the retina. In addition, projects associated primarily with the Bioengineering Research Partnership will be advanced such as efforts to image human ganglion cells noninvasively as well as retinal pigment epithelial cells in retinal disease.

Year 9 Milestones

- Microstimulate the Cone Mosaic with Flash Location Recorded.
- Exceed the Diffraction Limit in AO Retinal Imaging.
- Image Adolescent Photoreceptors.
- Image the Cone Mosaic of Patients with Inherited Macular Diseases .
- Imaging Radial Peripapillary Capillaries.
- Characterize the normal human RPE cell mosaic *in vivo*.
- Image Primate Ganglion Cells with AAV vector using the Fluorescence Adaptive Optics Scanning Laser Ophthalmoscope.
- Construction of a DIC AOSLO to image ganglion cells in humans noninvasively.
- Image photoreceptors in retinitis pigmentosa.

Indiana University

The group at Indiana led by Don Miller has developed two high-resolution retina cameras based on conventional flood-illumination and fiber-based spectral-domain optical coherence tomography (SD-OCT). Both employ adaptive optics for dynamically correcting the ocular aberrations of the eye. In Year 9, they will extend the technical capabilities of both cameras to allow improved functional imaging of the retina. For the AO SD-OCT camera, technical improvements include integration of an ultra-broadband light source for 3 micron axial resolution, active axial tracking and correction, and short-burst imaging. The AO flood illumination camera will be integrated with a broadband light source for stimulating photoreceptors and will undergo a re-calibration of the AO system that will account for non-common path aberrations in the new science channel. The performance of the high-speed scientific CCD in the flood camera will be optimized by developing a more effective method for correcting background artifacts. Vision science experiments will be conducted with both cameras under the auspices of a National Eye Institute grant. Collaboration with engineering and vision expertise both in and outside the Center will accelerate camera development and vision science experiments.

Year 9 Milestones

- Integrate ultra-broadband light source into the AO-OCT camera for 3 μm axial resolution.
- Develop axial tracking and correction capability for the AO-OCT camera.
- Develop short-burst imaging capability for AO-OCT camera.
- Expand and improve imaging capabilities of AO flood illumination camera.

University of Houston

Adaptive Optics Scanning Laser Ophthalmoscope images of the living human eye are distorted by eye motion, and correction of the distortion provides a record of the eye movement that is an

order of magnitude more precise than comparably priced dedicated eye trackers. Additionally, the AOSLO allows for precise localization of stimulus elements on the retina because the scanning beam is also the stimulating beam.

In this project Houston plans to take advantage of these two features of the AOSLO to study how very small eye movements depend on the precise location of a target feature, and to study how subjects perceive the position of targets at various known retinal locations. Comparison between normal and amblyopic (“lazy eye”) subjects will provide insight into the development and organization of spatial coordinates in the human nervous system for perception and eye movement control.

Year 9 Milestones

- Submit publications on motion and fixation eye movement measures. Submit a proposal to another agency for continued support if not already obtained.
- Travel to Berkeley, to collect more data on normal and amblyopic subjects. Begin stabilized target experiments.
- Finish analysis and write-up on the comparison of preferred locus for perceived direction and eye movements. Collect more data on stabilized targets.
- Analyze data collected in third quarter and prepare presentations/publications.

Montana State University

Retinally stabilized stimulus delivery by the Adaptive Optics Scanning Laser Ophthalmoscope was made operational in early 2007 and put into first experimental use in Jonathan Horton’s lab at UC San Francisco in March, 2007. The instrument was used to deliver a stabilized visible stimulus to single cones of a macaque monkey while recording intracellular activity in the LGN of the animal. Response of specific LGN cells to fields on and immediately surrounding single cones were successfully recorded.

Though the stabilized stimulus delivery as implemented represents the state-of-the-art it is still less perfected than desired. The fundamental limitation in the precision of the stabilization is a 6 millisecond lead time from the last estimate of target position to the time of delivery of the stimulus. Of this, only 1.5 msec is computation by the MSC-based target location prediction algorithm. The rest is some combination of hardware and possibly operating system delays. In principle, once the target location is computed, it should be possible to deliver the stimulus in 2 msec or less. Reducing the delay from position computation to stimulus presentation significantly reduces the uncertainty of retinal position and hence inaccuracy of the stimulus delivery. The main objective of MSU’s Year 9 research is to achieve delays of 2 msec or less. The secondary objective is to continue to add and refine the capabilities of the software that are necessary to making it a practical experimental tool.

Aside from neurophysiological experimentation, the stabilized stimulus delivery capability has already prompted planning for a variety of newly possible visual psychophysical experiments as well as opening the door to improving existing clinical applications, such as microperimetry, and possibly allowing new clinical applications. Year 8 of this project saw dramatic advancement from the Year 7 results, well ahead of schedule, of both the stabilized video presentation and prescribed stabilized stimulus delivery. The software refined during this period has been in practical experimental use and has set the stage for the proposed research. The first experimental use at UCSF as described above, has resulted in a list of features to facilitate experimental application which will start to be implemented as part of the Year 8 effort. In general, the project is approximately a year ahead of the schedule anticipated in Year 7.

Year 9 Milestones

- Reduce prediction time for stabilized stimulus delivery from 6 msec to 2 msec
- Add and refine capabilities of the software to make it useful and practical experimental tool

Iris AO

Year 9 Milestones

- Determine how best to test the Iris AO DM in Prof. Roorda's lab.
- Demonstrate 30 Hz-sampling-rate closed-loop control on the human eye.

Boston Micromachines Corporation

With the successful completion of the MEMS DM actuator arrays capable of 8 μ m of stroke, a mirror layer will be fabricated on the top surface. This mirror layer will complete the fabrication of the devices and allow implementation into ophthalmic imaging systems. The challenge with this mirror layer will be the balancing of the thin film stresses intrinsic in surface micromachining to produce a mirror with good surface finish and acceptable operating parameters. As mentioned, the actuator layer for this device will be half that of heritage devices. The effects of this thin film on topography are unknown. The mirror layer will also have to be thinner than on the heritage device for actuation voltages less than 300V and lower influence functions (mechanical cross coupling between adjacent actuators).

Year 9 milestones

- No CfAO funding for year 9 was sought for this project

III - EDUCATION

III.1a Educational Objectives

The mission of the CfAO Education and Human Resources (EHR) program is to use the Center's unique resources to promote institutional and cultural changes that will broaden student access to CfAO related fields. A range of programs has been developed and implemented focusing our efforts on the overall mission. The impact of CfAO EHR activities is measured by our success in each of four interwoven strategies:

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

III.1b Performance and Management Indicators

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

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

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

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

- Number of CfAO members involved in CfAO EHR
- Number of CfAO members that incorporate new teaching or mentoring strategies into their practice
- Number of CfAO graduate students and postdocs who implement inquiry based teaching strategies
- Number of CfAO graduate students and postdocs who move into faculty positions, and incorporate inquiry based teaching strategies
- Number of new research proposals that include EHR components due to affiliations with CfAO
- Number of communications that include research and EHR

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

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

- New mechanisms for engaging relevant communities in the CfAO and CfAO related fields

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

- Number of underrepresented undergraduates participating in CfAO activities (research and education)
- Number of underrepresented undergraduates retained in STEM⁷ education or careers
- Number of underrepresented undergraduates advanced into CfAO, and CfAO related, graduate programs
- Number of underrepresented graduate students participating in CfAO activities (research and education)

III.1c Problems Encountered Reaching Education Goals

The primary challenge faced by the education theme is in transitioning successful activities to programs that are sustainable after Year10. Significant effort has been applied to this in Year 8, and will continue in the coming year. The activities developed by the education theme are interwoven and much of the success we believe comes from their incorporation into an integrated overall education program. Each of the individual activities have a high potential for continued funding, but core funding for the leadership of a cohesive, focused program is more difficult to identify. As a first priority, we are seeking long-term, institutional funds in preference to short-term grants. Gaining institutional support requires dedicating significant time meeting with administrators and aligning with local needs and politics. Progress has been made on many fronts, and we are increasingly optimistic that we will be able to reach our goal of establishing an educational legacy that goes far beyond the life of our NSF Center funding.

III.2a The Center's Internal Educational Activities

Professional Development Workshop (PDP)

Activity Name	Annual Professional Development Program
Led by	Lisa Hunter. Team includes: Candice Brown, Barry Kluger-Bell, Anne Metevier, Jason Porter, Lynne Raschke, and Scott Seagroves.
Intended Audience	CfAO graduate students and postdoctoral researchers; graduate students from CfAO institutions who commit to teaching in CfAO programs; some scientists and education partners
Approx Number of Attendees (if appl.)	40-50 participate each year (~50% are new each year; 50% returning for their 2 nd year or more)
http://cfao.ucolick.org/EO/PDWorkshop/	

Goals

- 1) Develop inquiry-based teaching skills in graduate students and postdoctoral researchers
- 2) Facilitate the incorporation of inquiry based teaching strategies in CfAO EHR programs
- 3) Develop partnerships and collaborations within the scientific, technical and educational community of Hawaii.
- 4) Build a community of practice amongst graduate students and postdoctoral researchers.

⁷ STEM – Science, Technology, Engineering and Mathematics

Project Description: The CfAO PDP is an ongoing, multi-year educational activity for science and engineering graduate students, postdoctoral researchers and CfAO education partners. The primary goal is to build a community of scientists/engineers who are proficient in teaching the processes of scientific inquiry, and who are better prepared to take on the educational roles expected of today's scientists and engineers. There are two integrated components of the PDP: the workshop, and a practical teaching experience in a one of CfAO's educational programs. Participants may return year after year in more advanced roles, and over the years the workshop has become a complex, multi-layered activity. The Maui Science and Technology Education Exchange (MSTEE) has been embedded within the workshop, and is an event that brings the CfAO together with the Hawaii technical and educational community to share accomplishments and new opportunities. Information on the past workshops can be found at: <http://cfao.ucolick.org/EO/PDWorkshop/current.php>.

Components of the PDP workshop

The core experience of the PDP is an intensive five-day workshop, which in 2007 transformed into two concurrent workshops – one for first year attendees, and the other for returning participants. Components of the workshop now include:

- **Comparing Approaches to Hands-On Learning:** Designed by the Exploratorium Institute for Inquiry (IfI), this unit gives participants a hands-on learning experience in three different ways, and is followed up by a reflective discussion on pedagogy and on matching activities to goals.
- **Learning Science Content Through Inquiry:** In this unit participants take on the role of a learner and engage in a laboratory unit on light and shadows that follows the classroom inquiry model developed by the IfI. After the inquiry activity, participants consider how their experience differs from the way that labs are typically taught.
- **How People Learn Science:** Participants engage in a facilitated small group discussion on a reading assignment from “How Students Learn: Science in the Classroom”⁸ Connections are also made to participants’ learning and teaching experience.
- **Designing Inquiry Activities:** This unit begins with “Backward Design”⁹ and focuses on participants learning about identifying and prioritizing learning goals. Participants learn about content, process, and attitudinal goals and then work for an extended period of time designing their own lab activity with expert consultation.
- **Advanced Elements of Inquiry Design:** Participants who have completed the above introductory design unit are exposed to a variation on an inquiry activity, discuss differences, and then lead a design team in developing and teaching an inquiry activity.
- **Designing for Diversity:** By way of readings, discussions, and visiting speakers, participants are exposed to issues of diversity, equity, and the cultural context for science.
- **Elements of Engineering Design:** In this unit, participants learn about designing lab

⁸ National Research Council (2005). *How Students Learn: History, Mathematics, and Science in the Classroom*. M.S. Donovan and J.D. Bransford, Editors. Washington, DC: The National Academies Press.

⁹ Wiggins & McTighe (1998). *Understanding by Design*.

activities that build engineering skills by redesigning a science focused activity to emphasize the engineering process.

- **Assessment: Rubric Design** Participants are introduced to rubrics and the general field of assessment.
- **Preparing to Facilitate Learning by Inquiry:** Participants “role play” a series of scenarios that are commonly faced in teaching through inquiry. After role playing, participants discuss strategies and tools for facilitating learning by inquiry.
- **Facilitating Learners in Inquiry Activities:** Participants learn about how teachers can facilitate learners in the inquiry process by either shadowing an expert teacher (introductory level), or facilitating with an expert (advanced level).



Fig. III.1 Participants at the Professional Development Workshop investigate puzzling optics phenomena during the “optics inquiry.”

Participation in the workshop is a beneficial experience; however, the follow-up teaching experience in one of CfAO’s “teaching labs” can be transforming. We have developed many opportunities for workshop participants to pilot their new teaching skills, and then reflect on their experience with peers. The combination of the workshop and the teaching experience has led to the development of many new inquiry activities and a cadre of reflective science teachers with proficiency in inquiry based teaching approaches.

Outcomes: Immediate responses to the workshop are determined through a post-workshop survey. A complete summary of the findings is available in a report prepared by our external evaluator, Julie Shattuck and Associates, at <http://cfao.ucolick.org/EO/PDWorkshop/strategic.php>.

One of the most significant gains reported by participants was the pre/post shift in how they felt about their abilities to construct an inquiry activity. Before the Workshop, only 29% reported having “some” or “a great deal” of capacity to create an inquiry lesson. At the conclusion of the Workshop, this number rose to 87% (see Figure 3.2).

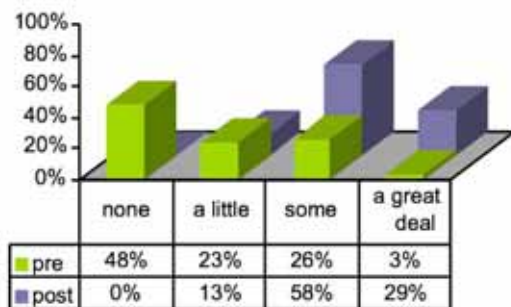


Fig III.2 Workshop participants' pre/post ratings of their capacity to design an inquiry activity for a teaching situation

After returning from the workshop, an increasing number of participants design new inquiry activities and/or teach an inquiry-based instructional activity. Workshop staff observe activities, reviews lesson plans, and debrief instructors to learn how they incorporated inquiry into their activities.

Table III.1: 2006 PDW Participants and their subsequent inquiry teaching activity

Last Name	First Name	Inquiry Teaching Activity	Role / Program
Ammons	Mark	AO workbench activities; Shadow Inquiry	Mainland Short Course; PDW; AO Summer School
Anderson	Sarah	Optics Inquiry	Big Island Short Course
Azucena	Oscar	Wavefront Engineering Activity	Mainland Short Course
Ball	Tamara		Ed. Researcher @ Mainland Internship
Cense	Barry		
Chomiuk	Laura	Star Clusters	COSMOS
Church	Candace	Astronomy Research Inquiry; Color, Light and Spectra; Shadow Inquiry	Hartnell Short Course; MCC Physics; PDW
Clare	Richard		
Cooksey	Kathy	Optics Inquiry; Color, Light & Spectra	COSMOS
Crowley	Brooke	3 Kinds of Hands-On Science	CILS/CfAO Sat. Open Lab for Cal Teach
Espinoza	Liz	3 Kinds of Hands-On Science	CILS/CfAO Sat. Open Lab for Cal Teach
Fernandez	Bautista	Wavefront Engineering Activity	Mainland Short Course; intern mentor
Fitzgerald	Michael	Shadow/Optics Inquiry	Intern mentor; 2007 PDW
Grieve	Kate	3 Kinds of Hands-On Science	Intern mentor; CfAO/CILS Cal Teach recruitment; PDW
Hansen	Charles		

Last Name	First Name	Inquiry Teaching Activity	Role / Program
Hartzog	Grant		Bio faculty @ UCSC
Hoffman	Mark	Color, Light and Spectra; Image Processing; Telescope Building	Maui Short Course
Howley	Kirsten		
Ishida	Catherine	Optics Inquiry	Big Island Short Course
Johnson	Jess	Wavefronts and AO	Maui Short Course
Konopacky	Quinn		
Laag	Eddie	Camera Obscura	Maui Short Course
Laird	Elise	Color, Light, and Spectra	Mainland Short Course
Langridge	Suzanne		
Lu	Jessica	AO workbench activities	AO Summer School
Martell	Sarah	Astronomy Research Inquiry	UCSC Sat. Open Lab
Martin	Joy	Shadow inquiry	2006 PDW
Montgomery	Ryan	Lenses and refraction; Color, Light, Spectra	Maui Short Course
Moth	Pimol	Astronomy Research Inquiry; Shadow Inquiry	Hartnell Short Course; 2007 PDW
Motomura	Harvey		Faculty @ HawCC CILS/CfAO Sat. Open Lab for Cal Teach;
Patel	Mira	3 Kinds of Hands-On Science	ED212 MCC faculty, astro lab course
Pye	John	Astronomy lab course	CILS/CfAO Sat. Open Lab for Cal Teach
Racelis	Alex	3 Kinds of Hands-On Science	Big Island Short Course
Rafelski	Marc	Optics Inquiry	Intern mentor
Rice	Emily		CILS/CfAO Sat. Open Lab for Cal Teach
Rose	Alex	3 Kinds of Hands-On Science	Mainland Short Course
Rossi	Ethan	Retinal anatomy; data interpretation	CILS/CfAO Sat. Open Lab for Cal Teach
Small	Jennifer	3 Kinds of Hands-On Science	Faculty @ Kauai CC
Takahashi	Francis		COSMOS
Trouille	Laura	Star Clusters	

III.2b Summary of Professional Development Activities for Center Students

1. Annual Professional Development Workshop – The workshop (more fully described in Section III.2a) builds teaching, collaborative teamwork, communication, and other important skills.
2. Summer School on Adaptive Optics – Courses are intended to convey the scope and application of adaptive optics to research. This is a professional development course for both astronomers and vision scientists. See description in Knowledge Transfer section.
3. Center retreats and workshops – Center students have multiple opportunities each year to participate in Center retreats and workshops, with many opportunities for presenting their

research. Our industry affiliates program meets at our retreats and is an excellent venue for students to make contacts in industry.

III.2c The Center's External Educational Activities

All our external programs focus on students from underrepresented groups. The Stars Sight and Science program is aimed at high school students.

The Mainland, Akamai and Big Island Internships focus on Community College students. These programs begin with a short course followed by summer internships.

Stars, Sight, and Science Program

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

GOAL

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

Project Description:

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

- Astronomy Today: Observing the Universe
- Human Vision: Photons, Proteins, and Perception
- Transferable Skills

This program is offered in conjunction with the California State Summer School for Mathematics and Science (COSMOS) program at UCSC. Beginning in Year 5, the COSMOS program has agreed to cover the majority of costs for *Stars, Sight and Science*, indicating the institutional commitment to this successful program. The CfAO now covers a small percentage of CfAO staff time and the costs associated with bringing in instructors from remote CfAO sites.

Stars, Sight, and Science focuses on middle to high achieving students from groups underrepresented¹⁰ in STEM, providing them with interdisciplinary, inquiry based experiences, and small group projects led by graduate student advisors. The CfAO instructional team includes lead instructors, project advisors, guest instructors, and a high school science teacher. The program uses adaptive optics as a starting point to foster an interest in related fields such as vision science, astronomy, engineering, and advanced instrumentation.

¹⁰ Underrepresented minorities defined here as Hispanic, African American, Native American, Pacific Islander.

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

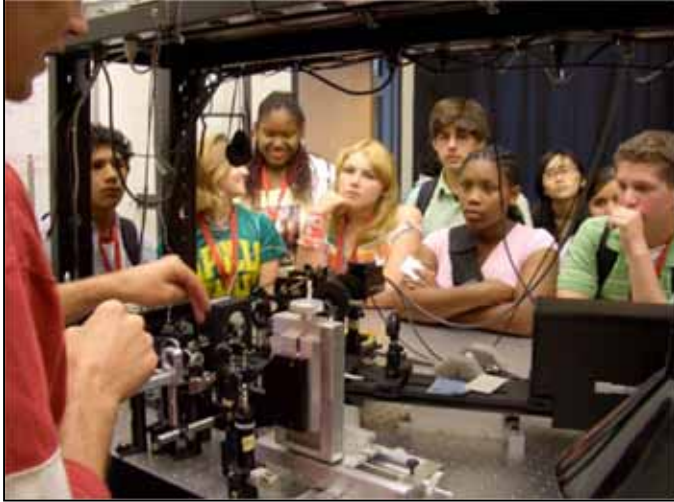


Fig. III.3 COSMOS students visiting Professor Austin Roorda's lab during a field trip to the UC Berkeley School of Optometry.

Outcomes:

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

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

Galaxy Project

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

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

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

Table Top Optics Inquiry

This inquiry was designed in 2001, and has been used each year since, with new inquiry facilitators rotated in to gain experience in the tools and strategies for teaching with inquiry. An excerpted description of the Lynne Rashke’s Table Top Optics Inquiry appears in Box 1 (next page)

Dissemination:

A publication¹¹, describing the overall COSMOS program includes a special 2-page section on CfAO entitled: “A special partnership: CfAO Stars, Sight, and Science.”

Mainland Internship Program

Activity Name	Four Year and Community College Internships
Led by	Lisa Hunter; Lead Staff: Hilary O’Bryan, Scott Seagroves
Intended Audience	Undergraduates, primarily from underrepresented groups, with an emphasis on community college students
Approx Number of Attendees (if appl.)	10-15 each year

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

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

A unique element of the Mainland Internship Program is our five-day short course that precedes the research experience. The goals of this course are to establish a community among the students; prepare them for the research environment; orient them to the CfAO; and teach them some of the background necessary for a successful experience in the multi-disciplinary environment CfAO.

¹¹ C. Moran, J. Roa, B.K. Goza, and C.R. Cooper, Success by Design: Creating College-Bound Communities (UC Santa Cruz EPC, Santa Cruz, CA), pp. 85-100.

Excerpt from Documentation of Optics Inquiry

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

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

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

Activity:

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

The short course prepares students for their coming research experience through a set of inquiry activities, laboratories, lectures, discussions, and small team problem solving. Topics include astronomy, vision science, engineering, research practices, and preparation for graduate school. The short course was developed by CfAO graduate students and has now become a model for three other short courses. The Mainland Short Course is one of CfAO's "teaching labs," providing opportunities for piloting new inquiry based teaching activities.



Fig. III.4 Mainland Interns using spectrographs during the "Color, Light and Spectra" inquiry at the Mainland Short Course

Summary of accomplishments

- The CfAO now has 3 graduate students who are from underrepresented minority groups. These graduate students are actively engaged in CfAO funded research and represent a significant increase, as the CfAO had not in the past had any underrepresented minority graduate students.
- The CfAO has improved the diversity of the UCSC Electrical Engineering Department: Three of the seven underrepresented minorities in the EE graduate program are from the CfAO (total of 53 graduate students in EE).
- Of the 63 participants to date, at least 52 (83%), are still on a STEM education/career path.
- Thirteen of these students are now in science, engineering, or math graduate programs (6 women; 11 underrepresented minorities).
- The Hartnell Astronomy Short Course taught by CfAO instructors is a successful recruitment tool, with 2 students from the course accepted into the 2005 and 2006 Mainland Internship Program, and 1 student in 2007. Hartnell has awarded the CfAO the Hartnell President's Partnership Award.
- Our partnership with the Hispanic Association of Colleges and Universities (HACU) awarded the CfAO an additional \$25,000 in 2004, \$37,500, in 2005 and 2006 for student support. HACU recruited 5 of the 9 students in the 2005 Mainland Program, and 4 of the 11 in 2006.

Mainland Internship Program: Goals

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

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

Table 3.1 shows the status of the 63 interns who completed the program between 2002-2006. At this time, 36 students are currently enrolled in a STEM program. Fifteen students have graduated with degrees in a STEM area. Our current STEM retention rate (those still on track as undergraduates, graduate students, or in the workforce) is at least 83%. It should be noted that this retention rate is not a final retention rate, as students are still enrolled, some at the community college level. Our goal is for 75% of our students to complete Bachelor's degrees and be retained in STEM.

Mainland Intern Graduate School Entry

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

The Mainland Internship Program represents a pool of prospective students for our graduate programs, taking advantage of the "grow your own" strategy. During the selection process, special attention is given to those students who have the academic qualifications and interests to enter graduate school. After running the program for several years, and a great deal of mentoring and advising, we have begun to see the Mainland Interns enter graduate school. We now have 13 students who with confirmed enrollment (or completion) in S&E graduate school, who are underrepresented minorities and women:

- Oscar Azucena, UC Santa Cruz, Electrical Engineering, Entered F2005, Cota-Robles Fellow
- Carlos Cabrera Andres, UC Santa Cruz, Electrical Engineering, Entered F2005
- Nella Barrera, UC Irvine, Mechanical & Aerospace Engineering, Entered F2006
- Arturo Cisneros, San Jose State University, Electrical Engineering, Entered S2007
- Rigo Dicochea, UC Santa Cruz, Electrical Engineering, Entered F2005
- Jesus Enriquez, San Diego State University, Astronomy, Entered F2006
- Bautista Fernandez, UC Santa Cruz, Electrical Engineering Master's program, Entered F2004
- Alex Gittens, California Institute of Technology, Applied and Computational Mathematics, Entered F2006
- Kerry Highbarger, Optical Engineering, Ohio State, Entered F2004
- Maribel Huerta, University of Houston, School of Optometry, Entered F2005
- Monica Pinon, UC Berkeley, School of Optometry, Entered F2005
- Jacyln Plandowski*, Electromagnetics, UC Los Angeles, Entered F2005
*Received Master's Degree in December 2006
- Amanda Young, Virginia Tech, Applied Math, Entered F2004

In addition we know of 9 undergraduates who will be graduating this June, and 3 have been accepted into graduate programs. A 2006 graduate has also been accepted. The students who have been accepted are:

- Sahar Kashef, UC Irvine, Mechanical & Aerospace Engineering, Entering F2007
*Graduated in June 2006

- Diana Lozano, choosing between the Biomedical Engineering Masters Program at the University of Rochester and the Physiological Optics Ph.D. Program at the University of Houston, Entering F2007
- Neil Mendoza, Dartmouth Medical School, Entering F2007
- Layra Reza, University of Washington in Seattle, Physics, Entering F2007

Table III.2: Status of Mainland Interns as of May 2007

	Number	A. Enrolled undergrad in STEM	B. Left college w/o degree	C. Switch ed to non- STEM	D. Eligible to apply to grad school	E. Applied to grad school	BA/BS	H. In grad school in STEM	I. Entered STEM workforce	J. Grad school in non- STEM	STEM
							G. BA/BS earned				L. On STEM path*
Men	28 (44%)	16	0	0	5	2	11	7	1	1	24(86%)
Women	35 (56%)	15	1	0	5	3	18	6	7	1	28 (80%)
Under-rep minority	46 (73%)	25	0	0	8	5	18	11	3	1	39 (85%)
Other ethnicity	17 (27%)	6	1	0	2	0	11	2	5	1	13 (76%)
TOTAL	63	31	1	0	10	5	29	13	8	2	52 (83%)
Under-rep group (women or minority)	60 (95%)										
Not under-rep	3 (5%)										

$$\infty L = A + H +$$

$$\infty$$

GOAL #2: *To develop linkages and partnerships that will broaden participation in CfAO related fields.*

Partnerships have been established with the following organizations:

Hartnell College, Salinas, California

Minority Serving Institution (MSI). See below, “Hartnell Astronomy Short Course”

Hispanic Association of Colleges and Universities (HACU)

HACU provided full financial support, including administrative costs for a total of \$8,000 each, for interns in 2004-2006. They also assist in student recruitment.

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

The Mainland Short Course was taught by five CfAO graduate students and postdocs: Mark Ammons (Lead, UCSC astronomy graduate student), Ethan Rossi (UC Berkeley Vision science graduate student), Oscar Azucena (past intern and UCSC EE graduate student), Bautista Fernandez (past intern and UCSC EE graduate student) and Elise Laird (UCSC astronomy post doc). All five instructors are participants in the Professional Development Program. where, a new inquiry on image correction was developed and was piloted at the Mainland Short Course.

Akamai Maui Internship Program

Activity Name	Four Year and Community College Internships
Led by	Lisa Hunter; Lead Staff: Hilary O'Bryan and Scott Seagroves
Intended Audience	Hawaii-based undergraduates, primarily from underrepresented groups, with an emphasis on community college students
Approx Number of Attendees (if appl.)	~12-15 per year

Web link: <http://cfao.ucolick.org/EO/internshipsnew/akamai/index.php>

The CfAO Akamai Internship is the outcome of a long-term investment in CfAO Hawaii partnerships. The internship brings together stakeholders from the Maui and Big Island communities with the common goal of increasing the participation of Hawaiians in CfAO related science and technology, and increasing the capacity of Maui Community College (MCC) to incorporate adaptive optics related technology into academic program offerings. The summer internship is preceded by a short course.

Akamai Optics Short Course

Akamai Interns are prepared for their research experience through the CfAO Optics Short Course, a 5-day intensive curriculum modeled after the Mainland Internship Short Course. This course is taught by CfAO graduate students and postdocs, and a MCC faculty member. The Short Course gives students a general background in optics and scientific processes through a set of inquiry based activities supplemented by lectures. In addition, internship hosts give a short talk on their work and what their assigned intern will be doing for a research project. Akamai interns receive credit for the Short Course through Maui Community College MCC (ETRO 193v).

Also see: <http://cfao.ucolick.org/EO/internshipsnew/shortcourses/mauisc.php>.

Research Experience

The Akamai Interns are placed at high tech industry sites (primarily the federal contractors on Maui for the Air Force) and at astronomical observatories. The following organizations hosted interns in 2003-2006 and will be encouraged to participate again in future years:

- Boeing
- Trex
- Akimeka
- Oceanit
- Maui High Performance Computing Center (MHPCC)
- Pacific Disaster Center
- Textron
- Northrop Grumman
- General Dynamics
- Institute for Astronomy, University of Hawaii
- Hnu Photonics

Akamai interns present their summer research at an AMOS Student Session held within the AMOS Technical Conference on Maui each September. The AMOS Student Session began in 2003 as a collaboration between CfAO, the Maui Economic Development Board, and the Air Force Maui Optical and Supercomputing Site (AMOS). This session fosters collaboration

between the technical and educational communities of Maui, and provides students with an opportunity to experience a professional conference. Family and other community members are invited to attend the student symposium, and we anticipate that this community participation will be better informed on technology issues and supportive of technologies in use on Haleakala.

Outcomes:

Summary of accomplishments:

- At least 89% (24 of 27) are on track (enrolled in a science or tech program or working in a science or tech field)
- At least 43% (13 of 27) of the interns are working in technical positions, 1 part-time and still enrolled in a technical major in college; 12 working full-time.
- Akamai interns are working at the following Maui organizations: Oceanit, Textron, MHPCC, HC&S, Oceanic Cable, and Cedric D.O. Chong & Associates, Spirent communications, PMRF.
- 6 students have now transferred to 4-year institutions, from a community college
- 2 students are now in graduate school.
- The CfAO and Maui Community College were awarded \$40,000 to develop a new astronomy course with AO components.

The CfAO has implemented a new AMOS Student Session, held within the AMOS Technical Conference established in 2003 and held every year since.

Akamai Internship Goals

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

To date, 27 students have completed the program, 13 are currently working in technical positions - full-time (12) and part-time and still enrolled (1). Two students are in graduate school.

Table III.3: Status of Akamai Maui Interns, as of 5/1/07

	#	%	A.Enrolled Comm. College	B. Received AA/AS	C. Undergrad in STEM at four year inst.	D. Undergrad non-STEM	E. Received BA/BS	F.Full Time in STEM workforce	G. In grad school	H. Total on STEM pathway*
Men	28	70%	4	7	10	0	4	10	1	24 (86%)
Women	12	30%	3	2	3	0	2	3	1	10 (83%)
Underrep minority	20	50%	5	7	5	0	2	7	0	17 (85%)
Other ethnicity	20	50%	2	2	8	0	4	6	2	17 (85%)
TOTAL	40		7	9	13	0	6	13	2	34 (85%)
Hawaiian Born	29	72%								
Underrep group (Women or minority)	25	62%								

*H=A+C+F+G

Below are the details of the 16 Maui Akamai students currently working in technical positions full-time (12) or part-time and still enrolled (4):

- Arthur Agdeppa, about to graduate in ECET at MCC, employed at Oceanit following his internship there, (Maui, HI).
- Ryan Baptiste, first employed as a technician at Northrop Grumman following his internship there, now moved home to Kauai and working in ITT at the Pacific Missile Range Facility (PMRF), (Kauai, HI).
- Sunny Cabello, employed as a computer operator with Maui High Performance Computing Center following her internship there (Maui, HI).
- Joe Curamen, employed as a computer operator at the U. of Arizona while enrolled for his BS in EE there (Tucson, Arizona).
- Delmar Dommino, employed in Support at Cingular Wireless, and volunteering as a PC tech at MCC (Maui, HI).
- Mark Elies, employed as an image data base creator with the MALT project (Maui, HI).
- Thomas Emmsley, employed as a computer operator / maintenance technician with Maui High Performance Computing Center (Maui, HI).
- Mike Escedy, employed as a technician/observer with Oceanit, following his internship there (Maui, HI).
- John Fujita, employed as a TA/computer technician with Maui Community College after completing his BS degree in biology (Maui, HI).
- Melina Kari, telecommuting from Maui as a product verification engineer with Spirent Communications (Maui & Honolulu, HI).
- Nathan Kimura, began a distance-learning Master's degree in CS with Columbia in 2006, employed as an associate algorithm developer with Textron, following his internship there (Maui, HI).
- Daniella-Dawn Manansala, employed at ITT Industries at Pacific Missile Range Facility (PMRF) in data display (Barking Sands, Kauai).
- Joshua Martin, employed as an electrical engineer with Cedric D.O. Chong & Associates, Inc (Honolulu, HI).
- Charles Oliveira, has been employed as an electronics technician with HC & S but could not be reached for this report (Maui, HI).
- Glenda Ramos, first employed at Akimeka after her internship there, now moving to the Main High performance Center (MHPCC) and still enrolled at MCC (Maui, HI).
- Victoria Sensano, employed Oceanit as a telescope operator technician while enrolled in the ECET program at Maui Community College (Maui, HI)

GOAL #2: *To develop linkages and partnerships that will broaden participation in CFAO related fields.*

The following partners have been established:

Maui Economic Development Board

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

Maui Community College

Maui Community College (MCC) is involved in all aspects of the Akamai Maui Internship. Mark Hoffman (ECET), John Pye (astronomy), Walette Pellegrino (Cooperative Education) are on the program advisory committee and are directly involved in all decisions, including program design,

student recruitment and selection, coordination with industry hosts, and program completion. In addition the program has benefited from the strong support of Chancellor Clyde Sakamoto and Dean Suzette Robinson. MCC offers credit for the Akamai Optics Short Course through the Electronics and Computer Engineering Technology program.

Institute for Astronomy, University of Hawaii

The Institute for Astronomy (IfA) joined the partnership through participation in the 2006 Maui Science and Technology Education Exchange (MSTEE). The IfA is now actively involved in mentoring Akamai students, and became formally affiliated with the submission of the Akamai Workforce Initiative (AWI) proposal to the NSF/AFOSR (see below). The IfA is currently in the process of hiring a part-time education staff member who will spend 25% time supporting our current activities. IfA graduate students have also joined our Hawaii-based instructional teams.

Air Force Maui Optical and Supercomputing Site

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

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

The Akamai Maui Short Course uses a range of inquiry-based teaching activities, and has provided a number of graduate students and postdocs teaching opportunities. The following activities were incorporated into the 2006 course, and were facilitated by Jess Johnson (Lead, UCSC graduate student), Ryan Montgomery (UCSC graduate student), Eddie Laag (UCR graduate student), Karrie Gilbert (UCSC graduate student), and Mark Hoffman (MCC, faculty member):

- Color, Light and Spectra Inquiry
- Camera Obscura and Sun Shadows
- Lenses and Refraction
- Building a Telescope
- Wavefront and Adaptive Optics

The 2007 Akamai Short Course will be led by Jess Johnson (Lead, UCSC astronomy graduate student), Ryan Montgomery (UCSC astronomy graduate student), Dave Harrington (UH Manoa graduate student), Isar Mostafanezhad (UH Manoa graduate student), and Mark Hoffman (MCC, faculty member).

The Akamai Optics Short Course has served as a very productive curriculum piloting project. A new instructional module teaching the fundamentals of color and light was piloted in the short course and has now been integrated into the regular MCC physics course. Each November several CfAO members assist in teaching this inquiry based unit, providing formal classroom teaching experience to the CfAO members, and enhanced teaching capabilities for MCC. In November 2004, Sarah Martell (Astro Grad at UCSC) and Kathy Cooksey (Astro Grad at UCSC), traveled to MCC to facilitate the inquiry in Hoffman’s course. In 2005, Candace Church (Astro Grad at UCSC) and Kathy Cooksey (Astro Grad at UCSC) facilitated at MCC. In 2006, Candace Church and Lindsey Pollack (UCSC Astro Grad) facilitated.

Hawaii Island Akamai Observatory Program

Activity Name	Hawaii Island Akamai Observatory Program
Led by	Akamai Observatory Short Course: Lisa Hunter & David LeMignant Akamai Internship Program: Lisa Hunter, Scott Seagroves, Hilary O'Bryan, and Sarah Anderson
Intended Audience	Hawaii state residents attending college
Approx Number of Attendees (if appl.)	10-14

The CfAO piloted the Hawaii Island Akamai Observatory Program in 2005, through a partnership with Mauna Kea Observatories, UH Hilo, and the UH Institute for Astronomy. A new part-time Internship Coordinator, Sarah Anderson, was hired with the support of the CfAO and Keck. Anderson assists with student recruitment, finding and briefing intern advisors, coordinating the short course, and many other logistical details that have been essential in implementing a program on the Big Island.

The program includes the Akamai Observatory Short Course and apprenticeships at Mauna Kea observatories, with a student symposium at the end of the program in July. For 2007, ten students have been accepted: 4 from UH Hilo; 2 from UH Manoa; 2 from Hawaii CC; 1 from Honolulu CC and 1 Hawaii resident enrolled on the mainland. Information on the program can be found at: <http://cfao.ucolick.org/EO/internshipsnew/bigislandintern.php>.

The Akamai Observatory Short Course (AOSC) is a sub-component of the Akamai Observatory Internship program. It is a five-day course that takes place in Hilo at the Institute for Astronomy (IFA) there, in Waimea at Keck Observatory, with an overnight field trip to Hale Po'Haku and the summit of Mauna Kea. The goals of the short course are to prepare students for observatory internships as well as to act as a "teaching lab" for CfAO graduate students and post docs to implement the inquiry techniques they learned in the Professional Development Workshop. The course is led by CfAO graduate students and post docs, CfAO education staff and Mauna Kea Observatory employees.

2006 AOSC Instructional Team

David Le Mignant, Lead, Keck Observatory Astronomer
Rich Matsuda, Co-Lead, Keck Observatory Engineer
Sarah Anderson, Keck Observatory Employee and CfAO coordinator
Catherine Ishida, Subaru Astronomer
Marc Rafelski, UCLA Astronomy Graduate Student
Candice Brown, CILS Director, UCSC
Malika Bell, CfAO, UCSC

Newspaper Articles about the Hawaii Island Akamai Program:

- Fall 2006 Issue of Keck Observatory Advancement Magazine: "Inspiring the Imagination" (http://keckobservatory.org/support/magazine/2006/sept/06sept_5.htm)
- West Hawaii Today, January 10, 2007: "Observatories offer summer internships- Akamai Program puts student astronomers on Mauna Kea"
- Hamakua Times, February 2007 Issue: "Summer Internships Available at Hawaii Island Observatories"

- Waimea Gazette February 2007: "Summer Internships Available at Hawaii Island Observatories"
- Hamakua Times April 2007: "Ready on Short Notice" Article on James Ah Heong and his AO bench fabrication project, a collaboration with UCSC graduate student Mark Ammons.

Hawaii Island Akami Conformance to Goals

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

To date, 23 students have completed the program. All twenty-three are on the STEM pathway: 15 are undergraduates enrolled in a STEM major, 2 are enrolled in graduate school in STEM fields, and 6 are employed full-time in the STEM workforce.

- David Luis: Completed his Bachelor’s degree in Electrical Engineering from UH-Manoa in Fall 2006 and is now a research support electronics technician with the Institute for Astronomy at Kula, Maui.
- Michelle Darrah: Completed her Bachelor’s degree in Astronomy from UH-Hilo in Spring 2006 and is now a research associate at the Institute for Human and Machine Cognition in Florida, while also studying for the Physics GRE and preparing for graduate school.
- Vinya Agluba: Completed her Bachelor’s degree in Electrical Engineering from UH-Manoa in Spring 2006 and is now a manufacturing engineer at Boeing in Mesa, Arizona.
- James Ah Heong: Completed his Associate’s degree at Hawaii CC. Currently, he is an adaptive optics research associate in the Laboratory for Adaptive Optics at UC-Santa Cruz. This work is also earning him course credit towards his degree in Electrical Engineering at UH-Hilo.

Table III.3. Status of Hawaii Island Akamai Interns.

	#	%	A. Enrolled in Community College	B. Received AA/AS since internship	C. Undergrad In STEM at four year institution	D. Received BA/BS since internship	E. In graduate school	F. Full Time in STEM workforce	G. Total on STEM pathway*
Men	15	65%	0	2	10	4	2	3	15
Women	8	35%	1	0	4	3	0	3	8
Underrep Minority	8	35%	0	1	6	2	0	2	8
Other Ethnicity	15	65%	1	1	8	5	2	4	15
TOTAL	23	100%	1	2	14	7	2	6	23
Underrep group (Women or	14	61%							

	#	%	A. Enrolled in Community College	B. Received AA/AS since internship	C. Undergrad In STEM at four year institution	D. Received BA/BS since internship	E. In graduate school	F. Full Time in STEM workforce	G. Total on STEM pathway*
Minority)									
Hawaiian born	13	57%							

*G=A+C+E+F

GOAL #2: To incorporate inquiry-based teaching into CfAO related fields, by providing “teaching lab” for newly trained instructors to gain experience and pilot instructional material.

The 2006 AOSC included an optics inquiry, originally designed by Scott Severson and Lynne Raschke of UCSC and then refined at the 2005 and 2006 PDWs. It was facilitated by Catherine Ishida, Sarah Anderson, Candice Brown, and Marc Rafelski.

For 2007, again an AOSC inquiry team met and planned at the PDP Workshop to re-align the inquiry activity with the goals of the course, in consultation with the lead instructional team and experienced PDP participant Patrik Jonsson of UCSC. This summer the AOSC inquiry activity will be led by Mike McElwain, Emily Rice, and Steve Rodney.

Mainland Courses

Hartnell Astronomy Short Course

Activity Name	Hartnell Astronomy Short Course
Led by	Anne Metevier & Lisa Hunter
Intended Audience	Community college students and high school seniors
Approx Number of Attendees (if appl.)	15-20 annually

Web link: <http://cfao.ucolick.org/EO/internshipsnew/shortcourses/hartnellastronomy.php>.

A continuing Astronomy Short Course, The Distant Universe, was taught at Hartnell College, Salinas CA, a local minority serving community college in June 2004, August 2005, and August 2006. This course was aimed at entering and enrolled community college students. Dr. Anne Metevier has been the lead on this project, and received an NSF Postdoctoral Fellowship that includes her participation in the Hartnell short course. A team of instructors assisted Anne in teaching this five-day intensive course, including, Pimol Moth (Hartnell astronomy faculty member), Andy Newton (Hartnell Planetarium Director), Candice Church (UCSC graduate student), Lindsey Pollack (UCSC graduate student), Jennifer Lotz (UCSC post doc) and a handful of others who assisted with selected activities. Anne has attended five CfAO Professional Development Workshops, and has used the experience to incorporate inquiry-based teaching into the short course in a variety of ways, making use of many of the previously designed CfAO instructional material as well as developing new activities. In 2007 the leadership of the Hartnell Short Course will transition to Candace Church, UCSC Astronomy Graduate Student.

The Galaxy Research Inquiry, developed by a team led by Anne Metevier, was piloted at the Hartnell Astronomy Short Course in June 2005. Students in the Astronomy Short Course receive 1 unit through the Physics Department at Hartnell College. Details on The Distant Universe can be found at:

<http://cfao.ucolick.org/EO/internshipsnew/shortcourses/hartnellastronomy.php>.

III.2d Integrating Research and Education

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

- To date, 63 undergraduates have worked on CfAO related research (2002-2006 student cohorts).
- Fifteen high school students and one high school teacher participated in *Stars, Sight and Science* each year, a course on vision science, astronomy, and optics.
- CfAO graduate students and postdocs participate in the Maui technical and educational community, at the annual Maui High Tech Industry Education Exchange.
- The CfAO has developed four new short courses covering CfAO related topics
- CfAO members have developed many new inquiry-based instructional activities, including:
 - Variable star project and inquiry activity (Stars, Sight and Science)
 - Galaxy Project (Stars, Sight and Science)
 - Color and Light (Stars, Sight and Science)
 - Color, Light and Spectra (Mainland Internship Short Course)
 - Color and Light, version 2 (Akamai Short Course)
 - Table Top Optics (Stars, Sight and Science)
 - Camera Obscura (Akamai Short Course)
 - Lenses and Refraction (Akamai Short Course)
 - Photodiode Activity (Akamai Short Course)
 - Physiology of the Eye (Rochester Saturday Open Lab)
 - Color Vision Inquiry (Rochester Saturday Open Lab)
 - Visual Illusions (Stars, Sight and Science)
 - Retinal Anatomy (Mainland Internship Program)
 - Galaxy Research Project (Hartnell Short Course and UCSC Saturday Open Lab)
 - Image Correction & Engineering Processes (Mainland Short Course)

III.2e Conformance to Metrics

The metrics have been described in Section III.1b. Conformance to these metrics was described in previous sections under outcomes for each activity.

III.2f Plans for Year Nine

Annual Professional Development Program

The PDP has attracted a great deal of interest in the past few years, and has stimulated a range of ideas for serving graduate students, faculty members, professional scientists, and even undergraduates. It is also under consideration as a tool for curriculum development. Currently, the

PDP serves both Hawaii-based and California-based CfAO programs, and both communities have expressed interest in increasing participation. However, a reduced CfAO budget in Years 9 and 10 necessitates holding the workshop at a location that will have much lower travel costs. If additional funds can be raised, the workshop will be held on Maui as it has been for the past six years.

Institute for Scientist and Engineer Educators (ISEE)

Based on results from the CfAO strategic planning meeting (Half Moon Bay, August 2005), a working group formed to explore institutionalizing the PDW by joining efforts with the Center for Informal Learning and Schools (CILS). Lisa Hunter, Candice Brown, Rod Ogawa, and Claire Max have been meeting regularly, to plan the new Institute for Scientist and Engineer Educators (ISEE) at UCSC. The team has met with many UCSC administrators and stakeholders and has made progress in developing ISEE, but not as quickly as was hoped. Additional staff time is needed to develop this interdisciplinary, cross-divisional, unconventional program, and is part of the plans for Year 9.

A proposal for UCSC campus funding was submitted in June 2007. The proposal requests “bridge” funding to assist in developing ISEE.

Stars, Sight and Science

Stars, Sight and Science will continue with declining CfAO funding, in preparation for a fully institutional supported program by UCSC Year 10. We will continue the strong link with the Professional Development Workshop, using it to develop instructional activities for Stars, Sight and Science.

Mainland Internship Program

A major focus in the coming years will be to contribute to the knowledge base on the impact of undergraduate research experiences, through documentation and a new research project led by Tamara Ball, a graduate student in the Education Department at UCSC, co-advised by Lisa Hunter. We are also part of a new study, ASiLS (Assessing Science Inquiry and Leadership Skills), which explores how students gain inquiry and leadership skills during research experiences, and how the development of those skills affects their educational and career progress.

Akamai Maui Internship Program

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

Akamai Workforce Initiative & Electro-optics Engineering Technology Degree

In November 2006 the CfAO, MCC, IfA, and MEDB submitted a proposal to the NSF and AFOSR for \$3.2M over five years. If funded, the Akamai Maui program would continue, as well as funding for ten participants per year in the CfAO Professional Development Program. The proposal is currently in review at the NSF. AFOSR has committed to \$125K/year for the 5 year period, if the NSF is willing to cofund.

Hawaii Island Akamai Observatory Program

Based on the success of the fully implemented pilot program in 2005, we will continue it with a 20% time local coordinator. We have significantly increased the participation of Mauna Kea observatories this year and are very hopeful that this program will grow to be part of the observatory community outreach.

Hartnell Astronomy Short Course

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

IV. KNOWLEDGE TRANSFER

IV.1. Knowledge Transfer Objectives

The knowledge transfer activities focus on enhancing the Center's ability to fulfill its research and education goals as summarized in the CfAO mission statement: "To advance and disseminate the technology of adaptive optics in service to science, health care, industry, and education." In Year 8, the CfAO has continued to emphasize knowledge transfer by employing strategies articulated in its mission statement:

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

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

Performance and management indicators

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

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

IV.2. Problems

An ongoing challenge for the CfAO knowledge transfer activity is the exchange of information with industry: both the dissemination of CfAO research results to a broad cross section of the industrial community, and the determination of industrial issues which might best be served by this research. Our strategy during the first 5 years of the Center was to invite a broad cross-section of industry participants to Center events, particularly to our Center-wide retreats in the spring and fall of each year. The main goal of this involvement was to catalyze specific research collaborations with industrial partners. In Year 6, we began to concentrate on more specific collaborative activities with industry partners with whom we had established strong ties during the previous 5 years. This successful strategy has been carried forward in Year 8. Based on our experience in the first 6 years, we believe that strong collaborations with specific industry partners are most beneficial to both the industrial and academic participants. We continue to target new industrial partners in specific areas as appropriate. In addition, dissemination of research results to the industrial sector has been improved through several new conferences, topical meetings and panel discussions in areas such as MEMS and vision science. Nevertheless, we continue to view increasing involvement of industry participants in Center research as both a goal and a challenge.

IV.3. Description of Knowledge Transfer Activities

We carried out a broad range of effective CfAO knowledge transfer activities during Year 8. These activities are summarized in the following sections, along with future plans for the Center’s knowledge transfer program.

Knowledge Transfer Activity	CfAO Summer School	
Led by	Scott Severson	
Participants		
	Organization Name and State	
1	Multiple organizations (see below)	

The CfAO holds an annual week long Summer School on adaptive optics, in Santa Cruz CA. The target audience is graduate students, postdocs, and industrial researchers. Emphasis is given to topics that are of interest to both astronomers and vision scientists. In 2007 there were approx. 80 participants - 41 graduate students, 3 post docs and 14 industrial researchers. There were approximately 20 lecturers and laboratory assistants as well. In 2007, the fee structure of the summer school was modified to make the program financially more self-sustaining, in anticipation of the end of NSF Center funding after 2009. This was achieved by charging amounts closer to current market rates for industrial participants. Based on the subsequent registrations, this transition appears to be proceeding successfully. In anticipation of more industrial attendees the lab content of the program has been increased to provide more “hands on” experience.

Knowledge Transfer Activity	Workshops	
Led by	Multiple leaders (see below)	
Participants		
	Organization Name and State	
1	Multiple organizations (see below)	

The CfAO sponsors workshops each year. These range from large formal sessions at international meetings to smaller special-topics discussions, Workshops in Year 7 included:

- Fall Science and Education Retreat, 16-19 November 2006, Yosemite, CA, Approx. 150 participants.
- “MEMS Adaptive Optics” Conference. Chair Scot Olivier, Co-Chairs Joel Kubby and Tom Bifano. Part of SPIE’s International Symposium on MOEMS-MEMS 2007, San Jose, CA, January 2007. Approx. 100 participants.
- Spring Retreat, UC Santa Cruz, 23-29 March 2007. Topic-based workshops including:
 - Electro-optics Curriculum Development
 - CfAO Internship Short Course Planning
 - Professional Development Program
 - AO for Psychophysical Research in Vision Science
 - Quantitative Astronomical AO Science
 - Science for the Next Generation of Adaptive Optics on the Keck Telescope
 - Laser Technology and Systems for Astronomy
 - Point Spread Functions for High-Contrast AO and Ground and Space Coronagraphy
- The Spirit of Bernard Lyot Conference, Co-Chairs James Graham and Paul Kalas, UC Berkeley, June 2007. Approx. 125 participants
- Gemini Conference, Vancouver June 2007

Knowledge Transfer Activity		AO test-bed for vision
Led by		David Williams
Participants		
1.	Jay and Maureen Neitz, PhD	Medical College of Wisconsin
2.	Ed Stone, MD	University of Iowa
3.	Phillip Kruger	SUNY School of Optometry
4.	Pablo Artal	University of Murcia
5.	Bill Merigan	University of Rochester, Ophthalmology M and D
6.	Mina Chung	University of Rochester, Ophthalmology M and D
7.	Wayne Knox	University of Rochester, Institute of Optics

A key goal of the CfAO is to make AO broadly accessible to the scientific and medical community. One way of achieving this is by making the vision AO systems developed within the CfAO available to research groups outside the CfAO. The Rochester vision AO system has been used by several research groups outside the CfAO in the past year. These include researchers from the University of Pennsylvania, the University of Murcia (Spain) and the University of Wisconsin.

Knowledge Transfer Activity		AOSLO Collaboration with UCSF
Led by		Austin Roorda
Participants		
1	Jacque Duncan, MD	UC San Francisco
2	Jonathan Horton, MD, PhD	UC San Francisco

Professor Roorda has built and developed an Adaptive Optics Scanning Laser Ophthalmoscope (AOSLO) system. He is collaborating with Dr. Jacque Duncan and using this system for clinical imaging of patients with inherited retinal disease. The research is jointly funded by the “Foundation Fighting Blindness” and a National Institutes of Health BRP. He is also collaborating with Dr. Jonathon Horton on “Combined AO Stimulus Delivery and Electrophysiology in Monkeys”. Both collaborations involve moving the actual AOSLO system to UCSF, which has occurred three times this year. Roorda’s group is now planning to build an AOSLO system for Dr. Duncan.

Knowledge Transfer Activity		AO microscopy for <i>in vitro</i> bio-imaging
Led by		Joel Kubby
Participants		
1	Bill Sullivan, Jin Zhang , Don Gavel	UC Santa Cruz
2	John Sedat, David Agard , Peter Kner	UCSF
3	Steve Lane, Scot Olivier	LLNL

We have begun a joint developmental/seed project with the NSF Center for BioPhotonics Science and Technology at UC Davis in the application of AO to microscopy for *in vitro* biological

research. This work links research groups at UCSF, UCSC and LLNL affiliated with two NSF Centers to explore the potential for advanced bio-imaging with adaptive optics.

IV.4. Other Knowledge Transfer Activities

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

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

CfAO members play leadership roles in professional societies concerned with adaptive optics, serve on organizing committees for international professional conferences on adaptive optics, and present results of CfAO research. The CfAO Associate Director for Knowledge Transfer continued to serve as the Chair of the SPIE Technical Group on Adaptive Optics, which helped disseminate information on AO to the professional optics community, mainly through meetings held during selected major SPIE conferences. Although SPIE has recently reorganized the Technical Groups into Online Communities, it continues to sponsor Technical Events at selected SPIE conferences, and an Adaptive Optics Technical Event has been organized for the 2007 Optics and Photonics meeting in San Diego, CA.

Collaborative program development has been a successful strategy for leveraging Center resources to enable research and development of adaptive optics beyond what would be possible with CfAO funding alone. This strategy is also a highly effective means of knowledge transfer since the new collaborative programs include participants both inside and outside the Center. The major collaborative program development activities in Year 8 were in the areas of ExAO, next-generation AO for Keck Observatory, ophthalmic instrumentation and biophotonic systems.

In the area of ExAO, CfAO Theme 3 has been responsible for bringing together additional institutions in the US and Canada, including the Hertzberg Institute of Astrophysics, the American Museum of Natural History, and the Université de Montréal, to work on system design, technology development, simulation and modeling of ExAO systems for the Gemini Telescope. A major outcome of this activity in Year 8 was the successful preliminary design review of the \$23.5M project to develop the ExAO system for Gemini.

The Next Generation AO (NGAO) system for Keck Observatory is in the conceptual design phase. This is a collaboration with Caltech and the Keck Observatory, and involves the entire Keck observing community.

In vision science, we have developed a new generation of portable vision science AO systems that are being used at partner medical facilities, such as the Doheny Eye Institute at USC, for evaluation in a clinical environment. This is extending the scope of possible collaborative activities by accessing unique capabilities and conditions at the partner sites, while further broadening the reach of AO into the clinical community.

In biophotonics, a group led by Tom Bifano at Boston University, along with participants from UCSC, UC Davis and LLNL, developed a concept to transfer key technology from the CfAO and the Center for Biophotonics Science and Technology to a new NSF Engineering Research Center for Advanced Biophotonic Instrumentation. A pre-proposal based on this concept was submitted to the NSF Engineering Research Center program.

IV.5. Future Plans

We plan to maintain our program of information dissemination while enhancing specific aspects and incorporating new efforts. We will continue to encourage our researchers to publish in a timely mode in the peer reviewed literature.

Specific areas of emphasis in collaborative program development in Year 9 will include AO for ophthalmic instrumentation, next generation AO for Keck Observatory, MEMS development, and biophotonic instrumentation.

V. EXTERNAL PARTNERSHIPS

V.1 Partnership Objectives

The fundamental objective of our partnership activities is to enhance the Center’s ability to fulfill its research and education goals. The CfAO is pursuing this objective through strategies articulated as part of its mission statement: leveraging our efforts through industry partnerships and cross-disciplinary collaborations and encouraging the interaction of vision scientists and astronomers to promote the emergence of new science and technology

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

Performance and management indicators

The following parameters are used to measure the success of CfAO partnership activities in meeting our objectives:

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

V.2 Problems

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

V.3 Description of Partnership Activities

Partnership Activity		Development of Advanced Ophthalmic Instrumentation	
Led by		David Williams	
Participants			
	Name of Organization	List Shared Resources (if any)	Use of Resources
1	University of Rochester (Lead)	Adaptive optics scanning laser ophthalmoscopes	Demonstrate value of AOSLO for clinical and science use
2	Lawrence Livermore National Laboratory		
3	University of California, Berkeley		
4	the Doheny Eye Institute at USC		
5	Indiana University		
6	Optos		

CfAO's PI at the University of Rochester is leading a NIH Bioengineering Research Partnership (BRP), which was awarded a 5-year grant in 2003 at the level of \$10 million. Five partner institutions share the funds; these are the University of Rochester, Lawrence Livermore National Laboratory, the University of California at Berkeley, the Doheny Eye Institute at USC, and Indiana University. The partnership is developing and assessing the value of adaptive optics scanning laser ophthalmoscopes for clinical vision research and patient care by studying the following: neovascularization in age-related macular degeneration and diabetic retinopathy; photoreceptors in retinal degenerative disease such as retinitis pigmentosa; ganglion cell bodies in glaucoma; individual retinal pigment epithelial cells; and blood flow in the smallest retinal capillaries. Four new scanning laser imaging instruments have been completed using MEMS-based adaptive optics developed by the CfAO. This instrumentation was selected for a 2007 R&D 100 award, through a program sponsored by Chicago-based R&D Magazine, which recognizes the 100 most technologically significant inventions in the U.S. each year. In a related development, the U.K. company, Optos, has made plans to incorporate adaptive optics in a wide field scanning laser ophthalmoscope using intellectual property held by Rochester and Houston. This licensing agreement was signed in Year 7 and a newly graduated Ph.D. from the University of Rochester group joined Optos to participate in this effort in Year 8. Also in Year 8, a 5-year, \$10M competitive renewal proposal was submitted to NIH that, if successful, would extend this work through 2013.

Partnership Activity		Optical Coherence Tomography with Adaptive Optics	
Led by		John Werner	
Participants			
	Name of Organization	List Shared Resources (if any)	Use of Resources
1	UC Davis (Lead)		Demonstrate the clinical utility of the combination of AO and optical coherence tomography (OCT)
2	LLNL		
3	University of Indiana		
4	Duke University		

Based on research activities initially sponsored by CfAO, UC Davis led a successful proposal in 2003 for a Bioengineering Research Partnership (BRP) Grant for \$5 million over 5 years. The proposal focuses on demonstrating the combination of AO and optical coherence tomography (OCT). The clinical utility of this combination, which should enable high-resolution imagery of the living retina with extremely high contrast ratios, is being evaluated. Achieving the highest possible contrast ratios in three-dimensional retinal images is important for the accurate visualization of many clinically important structures in the retina that have intrinsically low scattering cross sections, such as ganglion cells, which are damaged by glaucoma. Joint recipients of the grant are UC Davis, LLNL, Indiana University. During the fourth year of this project, we tested concepts for combining OCT with a scanning laser ophthalmoscope, enhancing polarization-sensitive OCT with AO, increasing axial resolution of AO OCT by compensating for ocular chromatic aberration, and completing a compact clinical AO OCT system. Also in Year 8, a 5-year, \$5M competitive renewal proposal was submitted to NIH that, if successful, would extend this work through 2013.

Partnership Activity	Micro-electro-mechanical systems		
Led by	Scot Olivier, Don Gavel		
Participants			
	Name of Organization	List Shared Resources (if any)	Use of Resources
1	A consortium, organized by the CfAO, to develop MEMS deformable mirror technology for adaptive optics for vision science and astronomy		

The CfAO continues to support and coordinate the work at several universities (UC Berkeley, Boston University), national laboratories (LLNL) and industrial partners (Boston Micromachines, Iris AO, AOptix) to develop MEMS deformable mirror technology for adaptive optics suitable for application to vision science and astronomy.

In Year 8, Boston Micromachines 140-actuator mirrors with approx. 4 μ m stroke are being used in 6 vision science instruments developed by CfAO partnership activities, and Boston Micromachines has now developed a device with 6 μ m stroke. AOptix 37-actuator bimorph mirrors with a 10-mm clear aperture and approx. 15 μ m stroke for focus correction are also in being used in Year 8 in 3 of the above vision science instruments. These AOpti mirrors are used in combination with the Boston Micromachines devices to increase the ease of using AO in a clinical environment. Iris AO has successfully demonstrated a 37 segment deformable mirror with 5 μ m stroke. Additionally, Boston Micromachines 1000-actuator mirrors are being tested in the ExAO test bed at the UCSC Laboratory for AO. These devices have been effective in reducing aberrations, initially at a level 1 μ m peak-valley from a phase plate based on atmospheric statistics, to less than 6 nm rms in the controlled spatial frequency range using a spatially filtered Shack-Hartmann wavefront sensor.

Partnership Activity	Lasers		
Led by	1. Edward Kibblewhite; 2. Deanna Pennington		
Participants			
	Name of Organization	List Shared Resources (if any)	Use of Resources
1	University of Chicago, Palomar Observatory, CalTech, JPL, Lite Cycles		
2	LLNL, UCSC, Stanford		

Under CfAO funding, the University of Chicago worked with Lite Cycles to produce improved solid state laser heads for a sum-frequency laser, based on a design originally from MIT Lincoln Labs. The development and testing phase of the laser was successfully completed in Year 5 and the laser was shipped to Palomar Observatory for deployment, which was successfully completed in Year 6. In Year 7, the system was integrated with the Palomar AO system, in collaboration with CalTech and JPL, and successfully tested on the sky. In Year 8, the system has been used successfully for “shared-risk” science observation with members of the Palomar Observatory scientific community.

LLNL has a project within the CfAO to study fiber lasers. Complementary aspects of this work have been supported by internal funding at LLNL. LLNL also has a grant from the NSF Adaptive Optics Development Program to extend this fiber laser work to a pulsed format more suitable for use on giant (30-m class) telescopes that will require multiple laser beacons. In Year 7, 3.8 W of

output power was generated at 589 nm in a pulsed format. Significant industrial contacts have been established to produce the new custom technology components required for this research, namely Nufern, Crystal Fibre in Denmark, and PSI. There have been discussions with Actinix and Neolight regarding commercialization of this fiber laser system. In Year 8, the focus has been on preparing to deploy the system on the 1-meter Nickel Telescope at Lick Observatory, for testing with a MEMS AO system being developed for this telescope as part of the NSF-supported “Villages” project.

V.4 Other Partnership Activities

In the area of design of AO systems for giant segmented telescopes, CfAO previously cosponsored a working group with NOAO to produce a national AO technology development roadmap. This roadmap was used by the NSF to initiate an Adaptive Optics Development Program, which began in 2004 with an initial budget of ~\$3M which was used to support 6 projects. CfAO researchers lead 2 of these projects, and 2 others involve CfAO personnel. In addition, many CfAO institutions have been active in working on design concepts for AO systems on giant segmented mirror telescopes as part of the California Extremely Large Telescope (CELT) project sponsored jointly by the University of California and CalTech. In Year 5, the CELT team joined with the U.S. and Canadian national efforts in giant segmented telescope design. The combined effort is now called the Thirty Meter Telescope (TMT) project, and support for a preliminary design phase at the level of \$35M has been received from the Moore foundation. The Canadian National Science Foundation has also contributed funding for complementary and coordinated work in Canada. The CfAO Theme on AO for Extremely Large Telescopes is coordinating its basic research with the goals of the TMT AO design effort.

V.5 Future Plans

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

VI. DIVERSITY

VI.1a Objectives.

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

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

VI.1b Performance and management indicators

PARTNERSHIPS & LINKAGES. Develop linkages and partnerships that broaden participation in the CfAO and CfAO sites. The success metrics are:

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

PEOPLE. Broaden participation of CfAO and CfAO fields by advancing students from underrepresented groups. The success metrics are:

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

VI.1c Challenges in making progress

The challenge faced by the CfAO can be seen throughout U.S. STEM graduate programs: women, underrepresented minorities, and U.S. citizens in general, are not pursuing doctoral degrees at the level appropriate to their representation in the U.S. college age population. For some of our sites, the challenge is finding students from underrepresented groups, for other sites it lies in finding U.S. students from any ethnic group or gender. For the past few years we have focused our efforts on training undergraduates through our internship programs. Our efforts have resulted in three CfAO undergraduate interns who are now CfAO graduate students, actively engaged in our research, and tens of other former interns still in the undergraduate pipeline.

VI.2a Activities and impact

Diversity initiatives and activities are integrated throughout the CfAO EHR theme. However, the most significant effort is at the undergraduate level through CfAO's internship programs and short courses. The CfAO has chosen to focus on the undergraduate (including community college) level and the transition from the bachelor's level into graduate studies due to the low

entry and persistence rates of underrepresented groups in CfAO related fields at the undergraduate level. Although we continue our recruitment efforts at the graduate level, our early efforts made it clear that with so few prospective graduate students from underrepresented minority groups, our efforts would be most effective at the undergraduate level. The following programs and activities (fully described in the Education section of this report) are focused on increasing the diversity of the CfAO and CfAO related fields:

Mainland Internship Program

Summer research experiences for undergraduates (4-yr and community college). The goal of the program is to retain and advance students from underrepresented groups in CfAO related fields. From 2002-2006, 63 students have been accepted into the program (73% underrepresented minority [URM]; 62% female; 95% URM or female). Of those 63, at least 52 (83%), are still on a STEM education/career path. Thirteen of these students are now in science, engineering, or math graduate programs (6 women; 11 URM).

The CfAO itself now has 3 graduate students who are from underrepresented minority groups. These graduate students are actively engaged in CfAO funded research. This represents a significant increase, as the CfAO had not in the past had any underrepresented minority graduate students.

The CfAO has significantly impacted the diversity of the UCSC Electrical Engineering Department: three of the seven underrepresented minorities in the EE graduate program are from the CfAO (total of 53 graduate students in EE).

Akamai Maui Internship Program

Summer research experiences for college students who are Hawaii residents, or from Hawaii and studying on the mainland. The goal of the program is to retain and advance students in technical and scientific fields relevant to the state of Hawaii. In 2003-2006, 40 students were accepted into the program (50% URM; 30% female; 63% URM or female; 100% Hawaii residents or Hawaii residents studying on the mainland. Of the 40 participants:

- 34 (85%) are “on track” (enrolled or working in S&E)
- 16 (40%) are working in S&E
- 2 are in S&E graduate programs

Hawaii Island Akamai Observatory Program

Internship program implemented in 2005, based on the same model as the Mainland and Maui. To date, 23 students have completed the program (35% URM; 35% women; 61% URM or women). All twenty-three (100%) are on the STEM pathway:

- 15 are undergraduates enrolled in a STEM major
- 2 are enrolled in graduate school in STEM fields
- 6 are employed full-time in the STEM workforce.

Hartnell Astronomy Short Course

A continuing Astronomy Short Course, The Distant Universe, was developed by the CfAO and has been taught at Hartnell College, a local minority serving community college since June 2004. This course is aimed at entering and enrolled community college students and intended to motivate students to pursue physical science and engineering degrees, and to encourage students to apply for the CfAO internship program.

A total of 45 students have now completed the course. One of the primary goals for the short course is to recruit Hartnell students for the CfAO intern program, and establish a long-term

pathway between Hartnell and UCSC. Table 1 shows the status of the short course attendees who applied to our internship.

Table 1: Status of Hartnell Short Course Attendees who applied to CfAO Internship

	# attending course	# applied to internship	# accepted to internship	# on internship waiting list
2004	19	4	2	2
2005	12	3	2	1
2006	14	1	0	0

*2 Past Hartnell Short Course students applied for the 2007 Mainland Internship Program and 1 was accepted.

CfAO Graduate Fellowship

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

CfAO Post-Bac Fellowship

Fellowship for prospective graduate students with BA/BS degrees. The goal is to advance underrepresented minority students into CfAO graduate programs. We piloted this program in 2004, cost-sharing the fellowship with Keck Observatory through their AODP grant from the NSF. The student spent the 2004-2005 academic year preparing for graduate school and participating in research under the supervision of Jerry Nelson (UCSC) and Sean Adkins (Keck). He is now enrolled in the engineering doctoral program at UCSC and works on CfAO funded research in the area of MEMS.

Participation in minority serving organizations

The CfAO has participated in the SACNAS (Society for Advancement of Chicanos and Native Americans in Science) program for the past four years. The outcomes include applications to our Mainland Internship Program and closer connections to other minority serving organizations. For example, through the SACNAS conference we met representatives from HACU (Hispanic Association of Colleges and Universities), who funded three of our Hispanic interns, and directly recruited two of our interns in 2004, four in 2005, and four in 2006.

Stars, Sight and Science

Four-week residential science program for students from minority serving and low college-going-rate California high schools. The goal of this program is to motivate high school students to pursue science in college. The CfAO provides an instructional team each year.

VI.2b&c Student Recruitment: Activities and Lessons Learned

A significant amount of time and resources are spent each year in the identification and recruitment of high achieving students from underrepresented groups, including women and minorities, but with a much stronger focus on minorities due to the lack of minorities in our graduate programs. Recruitment efforts include college visits, attendance at national conferences, and a range of other activities.

Recruitment for Mainland Internship Program

The following points summarize recruitment outcomes:

- In 2007 we had 84 complete applications compared to 67 in 2006 and 52 in 2005.
- Of the 10 students who began the 2007 program, 10% found out about the program from the internet, 20% found out from MESA, 30% from a past participant or fellow student, 10% from a faculty member/counselor and 20% from a CfAO representative.
- Our attendance at the SACNAS National Conferences yielded 3 applicants, but none that were accepted into the program.
- Now that the program is in its 6th year a significant amount of recruiting is done by contacts that we have created over the years. There are MESA coordinators, faculty, staff and past interns at colleges across the US that know about the program and encourage qualified candidates to apply. This can be seen in the following recruiting table: 21% of the applicants heard about the program from Faculty Members/Counselors, 27% from MESA or DEEP, and 10% from past participants or fellow students.

Table 2. Recruiting Activities: Fall 2006-Spring 2007

Where	Date	Description of Event	Number Applied	Number Accepted
Hartnell College	09/07	Past Intern, Percy Vigo, presented to the Hartnell Physics Club	NA	NA
UC Santa Cruz	10/07	Past Intern, Justin Griggs, presented to the Black Science Network	NA	NA
Tampa, FL	10/26/07	SACNAS Conference Booth Past interns attended	3	0
Houston Community College	11/07	Dr. Fernando Romero presented to several science classes	1	0
Various Locations	12/07	Sent emails and made calls to MESA Contacts	19	3
Skyline Community College	02/07	Past Intern, Nasim Naderseresht, presented to other Skyline students	NA	NA
UC Santa Cruz	2/24/07	Inspiring Diversity in Science and Medicine	0	0
Various Locations	09/07 – 02/07	Past interns helped recruit fellow students for the program	8	1

Table 3. How students reported finding out about the Mainland Internship

Applicant Reported Source on Application	Complete Applications	Accepted and entered program
Faculty Member/Counselor	18	0
SACNAS	3	0
HACU	0	0
Internet	16	1
Flyer at school	1	1
CfAO Representative, class visit	7	2
Hartnell Astronomy Short Course	0	0
MESA (at CA Community Colleges)	19	2
DEEP (program at UCSC with three community college partners)	4	0
Past Participant/Fellow Students	8	3
Other	8	1
TOTAL	84	10

** note that some accepted students found out about the program in multiple ways. The total represents the actual number of completed apps and accepted students

Hawaii Akamai Program Recruitment

Significant efforts are also put into recruitment for the two Hawaii Akamai programs. Efforts include class visits, collaboration with faculty and student organizations, newspaper articles, and presentations by alumni. MCC, MEDB and CfAO hosted an Akamai Expo to recruit students for the Maui and Big Island Akamai program. This took place on January 26, 2007 at Maui Community College. Past interns and mentors from the Akamai program presented as a panel, Mark Hoffman (Maui Community College - MCC) led a tour of the ECET lab, and the CfAO Education staff helped participants start the online application.

Students were recruited for the Akamai Expo by MEDB, MCC, UH Hilo, UH Manoa, Society for Women Engineers and CfAO staff. The CfAO provided travel awards for students from neighboring Hawaii Islands to attend. This event was very successful in recruiting eligible students to apply to the program. Of the 34 people that attended the Akamai Expo, 17 people applied to an Akamai Program (Maui or Big Island).

To monitor our success in recruiting, we keep track of how Akamai participants (those who apply and are accepted into the program) learned about the program. Table 4 shows statistics for the Maui Akamai applicant pool, and Table 5 shows statistics for the Big Island applicant pool.

Table 4. Akamai Maui Internship Applicant Statistics

Applicant Reported Source on Application	Complete Applications	Accepted and entered program
Faculty Member/Counselor	12	4
Internet	3	0
Flyer	1	2
CfAO Representative, class visit or program	6	4
MEDB/SWE/WIT	3	0
Friend/Classmate/Family Member	3	0
Past Participant	2	2
Other	2	1
TOTAL	32	13

Table 5. Hawaii Island Akamai Internship Applicant Statistics:

Applicant Reported Source on Application	Complete Applications	Accepted and entered program
Faculty Member/Counselor	14	3
Internet	2	0
Flyer/Newspaper	3	0
CfAO Representative, class visit or program	7	6
Friend/Classmate/Family Member	2	0
Past Participant	3	1
MEDB/WIT	1	1
TOTAL	31	12

VI.2d Year 9 Diversity Plans

No changes in strategy from Year 8 are anticipated.

VII. MANAGEMENT

VII.1a Organizational Strategy:

The Center's Director is Professor Claire Max; the Managing Director is Dr. Chris Le Maistre. The Director has responsibility for the overall running of the Center and in particular the Center's research agenda. The Managing Director is in charge of Center operations. A University Oversight Committee reviews Center activities on an annual basis and reports to the Vice Chancellor for Research. The Center's Organization chart is shown in Appendix B.

The Center's Research is divided into Themes as discussed in Section II. The theme leaders report to the director. UC Santa Cruz is the headquarters for the Center and the business offices of the ten collaborating sites report to the Managing Director.

Internal Management of the Center is by an Executive Committee (not shown in the organizational chart). This Committee meets bi-weekly and consists of the Director, Managing Director, Associate Directors (Theme Leaders) and selected leading researchers. The Director is further advised on management issues and developments in the field of Adaptive optics, by an External Advisory Board. This Board also reports to the Vice Chancellor for Research.

Each researcher submits an annual report and proposal for future research. Proposals are reviewed by the Executive Committee and funding for new or continuing proposals is determined by progress made against milestones in the previous year and the quality of the research proposal. A Proposal Advisory Committee (PAC) meets with the Executive Committee to review the proposals and funding levels and to help with decisions on proposals that are on the edge.

The Theme leader for Theme 4 has changed. Austin Roorda from UC Berkeley has taken over from David WEilliams of the University of Rochester. David Williams will continue as a member of the Center's Executive Committee.

VII.1b Performance and Management Indicators.

All proposals are required to include benchmarks to enable determination of progress during the year. As described above all progress reports and proposals are reviewed each year by the Executive Committee with assistance from the PAC. The final funding decisions rest with the Director.

VII.1c Impact of Metrics

The stringent review of proposals and reports have over the years resulted in funding cuts to researchers and cancellation of projects. Conversely new projects have been funded in most years thus maintaining the vitality of the Center's research agenda.

VII.1d Management Problems

Apart from late receipt of NSF funds in Year 8, no other problems were. In Year 9 (the coming year), CfAO experiences a 17 percent reduction in funding. The Center's Program Review Committee has already met and reviewed and evaluated the Year 9 research proposals. Most of the PIs, in anticipation of the reduction in funding, had reduced their budgets accordingly. This in

conjunction with some further reductions and the elimination of some projects enabled the Review Committee to meet the budget constraints while maintaining the vitality of the research program.

VII.2 Management Communications

The Center’s Executive Committee meets biweekly. The UC Santa Cruz members assemble in the CfAO conference room and out of town members join by video or tele-conferencing links. The Executive Committee also meets periodically with NSF staff – Morris Aizenman (CfAO Technical Coordinator at NSF) and other members of NSF staff invited by Dr. Aizenman based on the agenda items to be discussed. These meetings are also held via video and tele-conferencing connections.

The Executive Committee consists of:

Claire Max	Director, UC Santa Cruz
Chris Le Maistre	Managing Director, UC Santa Cruz
Lisa Hunter	Associate Director (Leader Theme 1 – Education and Human Resources), UC Santa Cruz
Don Gavel	Associate Director (Leader Theme 2 – Extremely Large Telescopes), UC Santa Cruz
Scot Olivier	Associate Director Knowledge Transfer and Partnerships
Austin Roorda	Associate Director (Leader Theme 4 – Vision Science), UC Berkeley
Bruce Macintosh	Associate Director (Leader Theme 3 – Extreme AO), LLNL
Jerry Nelson	Former Director, Astronomy UCSC
Andrea Ghez	Member at large – Astronomy, UCLA
David Williams	Member at large – Vision Science, University of Rochester

Communication Problems No major problems associated with our electronic connectivity have been experienced. The video conferencing facility is used extensively for Executive Committee meetings, information exchange between researchers at different institutions, workshops, and also for interacting with summer interns who are at different research institutions on the mainland and the Islands of Hawaii.

VII.3. Center Committees

Internal Oversight Committee – University of California Santa Cruz

	Name	Affiliation
1	Bruce Margon	Vice Chancellor, Research
2	Stephen Thorsett	Dean of Physical and Biological Sciences
3	Michael Isaacson	Acting Dean, School of Engineering
4	Michael Bolte	Director, UCO/Lick Observatory
5	Lisa Sloan	Vice Provost, Dean Graduate Studies

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

The Program Advisory Committee

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

The External Advisory Board

	Name	Affiliation
1	Dr. Christopher Dainty	National University of Ireland
2	Dr. Ray Applegate	University of Houston, TX
3	Dr. Thomas Cornsweet	Visual Pathways Inc, Prescott, AZ
4	Dr. Norbert Hubin	European Southern Observatory, Munich
5	Dr. Fiona Goodchild	University of California, Santa Barbara, CA
6	Dr. Robert Fugate (Chair)	NM Institute of Mining and Technology, Chairman
7	Dr. David R. Burgess	Boston College, Boston, MA

VII.4 Changes to the Center's Strategic Plan

There have been no significant changes to the strategic plan since the last report. The Center as a whole, and the individual themes will continue to follow the strategic plans and Ghannt charts that were prepared at the commencement of Year 6. Currently, we are focusing on plans to continue all of the Center's activities after the NSF funding ends.

VIII. CENTER-WIDE OUTPUTS AND ISSUES

VIII.1a. Center Publications

Year 8 Peer Reviewed Publications

1. mkovics, M., I. de Pater, M. Hartung, F. Eisenhauer, R. Genzel and C.A. Griffith. "Titan's bright spots: Multiband spectroscopic measurement of surface diversity and hazes." *J. Geophys. Res.* 111: EO7S06
2. mkovics, M., M. Wong, C. Laver, and I. de Pater. "Detection of widespread morning drizzle on Titan." *Science* (2007) submitted.
3. Baraas, R., Carroll, J., Gunther, K., Chung, M., Williams, D.R., Foster, D., and Neitz, M. "Adaptive-optics retinal imaging reveals S-cone dystrophy in tritan color-vision deficiency." *JOSA A* 23. 5 (2007): 1438-1447.
4. Britton, Matthew. "The Anisoplanatic Point Spread Function in Adaptive Optics." *PASP* 118 (2006): 885-900.
5. Carroll, J., Drexler, W., and Roorda, A. "Advances in Retinal Imaging: Introduction." *J. Opt. Soc. Am. A* 24. 5 (2007): 1223-1224.
6. Chen L., Artal P., Gutierrez D., and Williams D. R. "Neural compensation for the best aberration correction." *Journal of Vision* (in press).
7. Chen, L., Kruger, P., Hofer, H., Singer, B., and Williams, D.R. "Accommodation with higher-order monochromatic aberrations corrected with adaptive optics." *J. Opt. Soc. Am. A* 23 (2006): 1.
8. Clare, R.M., Marcos A. van Dam, and A. H. Bouchez. "Modeling low order aberrations in laser guide star adaptive optics systems." *Optics Express* 15 (2007): 4711-4725.
9. Clare, R.M., and Ellerbroek, B.L. "Sky coverage estimates for adaptive optics systems from computations in Zernike space." *J. Opt. Soc. Am. A* 23 (2006): 418-426.
10. Close, L., Zuckerman, B., Song, I., Barman, T., Marois, C., et al. "New Masses and Ages for the Planetary Mass Binary Candidate Ophiuchus #11 (2MASS J16222521-2405139) and the Discovery of Another Very Wide, Low-Mass, Binary in Ophiuchus." (2MASS J16233609-2402209), *ApJ* 660, 1492. (2007)
11. de Pater, M. mkovics, A. H. Bouchez, M. E. Brown, S. G. Gibbard, F. Marchis, H. G. Roe, E. L. Schaller, and E. F. Young. "Titan Imagery with Keck AO during and after Probe Entry." *Journal of Geophysical Research* 11107 S05. (2006).
12. de Pater, I., S.G. Gibbard and H.B. Hammel. "Evolution of the Dusty Rings of Uranus." *Icarus* 180 (2006): 186-200.
13. de Pater, I., H.B. Hammel, S.G. Gibbard, and M.R. Showalter. "New dust belts of Uranus: one ring, two ring, red ring, blue ring." *Science* 312 (2006): 92-94.
14. de Pater, I., C. Laver, F. Marchis, H.G. Roe, and B.A. Macintosh. "Spatially Resolved Observations of the Forbidden SO a1, X3 Rovibronic Transition on Io during an Eclipse." *Icarus* (2007) in press.

15. Descamps, P., F. Marchis, T. Michalowski, F. Vachier, F. Colas, J. Berthier, D. Hestroffer, M. Assafin, P. Dunckel, K. Miller, M. Polinska, J.P. Teng-Chuen-Yu, A. Peyrot, R. Vieira-Martins, and M. Birlan. "Figure of the double Asteroid 90 Antiope from adaptive optics and lightcurve observations." *Icarus* 187 (2007): 482-499.
16. Digby, A.P., S. Hinkley, B. R. Oppenheimer, A. Sivaramakrishnan, J. P. Lloyd, M. D. Perrin, L. C. Roberts, Jr., R Soummer, D. Brenner, R. B. Makidon, M. Shara, J. Kuhn, J. Graham, P. Kalas, and L. Newburgh. "The Challenges of Coronagraphic Astrometry." *Astrophysical Journal* 650 (October 2006): 484-496.
17. Doble N., Miller D.T., Yoon G., and Williams D.R. "Requirements for discrete actuator and segmented wave-front correctors for aberration compensation in two large populations of human eyes." *Applied Optics* (in press).
18. Doble, N., D. T. Miller, G. Y Yoon, and D. R. Williams. "Deformable Mirror Requirements for Adaptive Correction in a Population of Normal Human Eyes." *Applied Optics* In Press.
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20. Duncan, J.L., Nakanishi, C., Gandhi, J., Zhang, Y., and Roorda, A. "High-Resolution in vivo Imaging of the RPE Mosaic in Eyes With Inherited Retinal Diseases." *Invest. Ophthalmol. Vis. Sci.* 47: E-Abstract 5666, 2007.
21. Duncan, J.L., Zhang, Y., Gandhi, J., Nakanishi, C., Othman, M., Branham, K.H., Swaroop, A., and Roorda, A. "High resolution imaging of foveal cones in patients with inherited retinal degenerations using adaptive optics." *Invest.Ophthalmol.Vis.Sci.* (in press).
22. Evans, J., et al. "Demonstrating sub-nm closed loop MEMS flattening." *Optics Express* 14 (2006): 5558.
23. Fitzgerald, M. P., and Graham, J. R. "Speckle Statistics in Adaptively Corrected Images." *ApJ* 637 (2006): 541
24. Graham, J. R., Kalas, P., and Matthews, B. C. "The Signature of Primordial Grain Growth in the Polarized Light of the AU Microscopii Debris Disk." *ApJ* 654 (2007): 595
25. Gray, D., Merigan, W., Wolfing, J., Gee, B., Porter, J., Dubra, A., Twietmeyer, T., Ahmad, K., Tumber, R., Reinholz, F., and Williams, D.R. "In vivo fluorescence imaging of primate retinal ganglion cells and retinal pigment epithelial cells." *Optics Express* 14. 16 (2006): 7144-7158.
26. Grieve, K. Tiruveedhula, P., Zhang, Y., and Roorda, A. "Multi-wavelength Imaging with the Adaptive Optics Scanning Laser Ophthalmoscope." *Optics Express* 14. 25 (2006): 12230-12242.
27. Grieve, K.F., Tiruveedhula, P., Rossi, E.A., and Roorda, A. "Measuring Intrinsic Retinal Signals With the Adaptive Optics Scanning Laser Ophthalmoscope." *Invest. Ophthalmol. Vis. Sci.* 47: E-Abstract 1954, 2007.
28. Grün, E., I. de Pater, M. Showalter, F. Spahn, and R. Srama. "Physics of dusty rings: History and perspective." *Planetary and Space Science* 54 (2006): 837-843.
29. Hinkley, S., B. R. Oppenheimer, R. Soummer, A. Sivaramakrishnan, L. C. Roberts, Jr., J. Kuhn, R. B. Makidon, M. D. Perrin, J. P. Lloyd, K. Kratter, and D. Brenner.

- “Temporal Evolution of Coronagraphic Dynamic Range and Constraints on Companions to Vega.” *Astrophysical Journal* 654 (January 2007): 633-640.
30. Hom, E.F.Y., F. Marchis, T.K. Lee, S. Haase, D. A. Agards, and J.W. Sedat. “An Adaptive Image Deconvolution Algorithm (AIDA) with Application to Multi-frame and 3D data.” *JOSA* (2007) in press.
 31. Hornstein, S., Matthews, K., Ghez, A. M., Lu, J. R., Morris, M., Becklin, E. E., Rafelski, M., and Bagano, F. K. “A Constant Spectral Index for Sagittarius A* During Infrared/X-ray Intensity Variations.” *ApJ* (2007) submitted.
 32. Kalas, P., Fitzgerald, M., and Graham, J. R. “Discovery of extreme asymmetry in the debris disk surrounding HD 15115.” Astro-ph/0704.0645 *ApJ* in press.
 33. Kalas, P. Graham, J. R., Clampin, M. C., and Fitzgerald, M. P. “First Scattered Light Images of Debris Disks around HD 53143 and HD 139664.” *ApJ* 637L (2006); 57.
 34. Konopacky, Q. M., Ghez, A. M., McCabe, C., Duchêne, G., and Macintosh, B. A. “Measuring the Mass of a Pre-Main Sequence Binary Star Through the Orbit of TWA 5A.” *AJ* 133 (2007).
 35. Konopacky, Q. M., Ghez, A. M., Rice, E. L., and Duchêne, G. “New Very Low Mass Binaries in the Taurus Star Forming Region.” *ApJ*, in press; astro-ph/0703567, 2007.
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- Sepulveda, R., Venkateswaran, K., and Zhang, Y. "What can adaptive optics do for a scanning laser ophthalmoscope?" Bulletin de la Société belge d'ophtalmologie 302. 4 (2006): 231-244.
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 62. Rossi, E.A., Grieve, K., and Roorda, A. "Visual Acuity and the Photoreceptor Mosaic." Invest. Ophthalmol. Vis. Sci. 47: E-Abstract 3175, 2007.
 63. Sabesan, R., Jeong, T.M., Cox, I., Williams, D.R., and Yoon, GY. "Vision improvement by correcting higher-order aberrations with customized soft contact lenses in keratoconic eyes." Optics Letters 32, 8 (2007): 1000-1002.
 64. Sheehy, C. D., McCrady, N. and Graham, J. R. "Constraining the Adaptive Optics Point-Spread Function in Crowded Fields: Measuring Photometric Aperture Corrections." ApJ 647 (2006): 1517
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 69. Soummer, R. and A. Ferrari. "Strehl ratio in adaptive optics images: statistics and estimation." (2007) accepted. Astrophysical Journal Letters.
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75. Vogel, C., D. Arathorn, A. Roorda, and A. Parker. "Retinal motion estimation and image dewarping in adaptive optics scanning laser ophthalmoscopy." Optics Express 14 (2007): 487- 497.
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Year 8 Books and Book Chapters

1. Marchis, F., J.R. Spencer, and R.M.C. Lopes. Io After Galileo Eds R.M.C. Lopes, and J.R. Spencer, Praxis-Springer, published, ISBN 3-540-34681-3, October 2006.

Year 8 Publications: Non-Peer Reviewed Papers

1. Berthier, J., F. Marchis, P. Descamps, D. Hestroffer, F. Vachier, F. Colas, C. Laver, M. Adamkovic, and I. de Pater. "(22) Kalliope I (Linus)." IAU Circular 776 (2006): 1.
2. Cense, Barry, Yan Zhang, Ravi S. Jonnal, Jungtae Rha, Weihua Gao, Mircea Mujat, B. Hyle Park, Johannes F. de Boer, and Donald T. Miller. "Ophthalmic imaging with adaptive optics polarization-sensitive spectral-domain optical coherence tomography." SPIE's 2007 International Symposium on Coherence Domain Optical Methods and Optical Coherence Tomography in Biomedicine XI. San Jose, CA. 20-25 January 2007.

3. Graham, J.R. and Macintosh, B., Doyon, R., Gavel, D., Larkin, J., Levine, M., Oppenheimer, B., Palmer, D., Saddlemyer, L., Sivaramakrishnan, A., Veran, J.P., and Wallace, K. "Ground-Based Direct Detection of Exoplanets with the Gemini Planet Imager (GPI)." ArXiv 0704 (2007): 1454.
4. Hornstein, S. D., Matthews, K., Ghez, A. M., Lu, J. R., Morris, M., Becklin, E. E., Baganoff, F. K., and Rafelski, M. "Infrared/X-ray intensity variations and the color of Sgr A*." JPhCS 54 (2006): 399.
5. Jones, Steven M., Scot S. Olivier, Diana Chen, S. Joeres, S. Sada, Robert J. Zawadzki, John S. Werner, and Donald T. Miller. "Adaptive optics ophthalmologic systems using dual deformable mirrors." SPIE's 2007 International Symposium on Coherence Domain Optical Methods and Optical Coherence Tomography in Biomedicine XI. San Jose, CA. 10-25 January 2007.
6. Jonnal, Ravi S., Jungtae Rha, Yan Zhang, Barry Cense, and Donald T. Miller. "High-speed adaptive optics functional imaging of cone photoreceptors at a 100 MHz pixel rate." SPIE's 2007 International Symposium on Ophthalmic Technologies XVII. San Jose, CA. 20-25 January 2007.
7. Le Mignant, D., R. D. Campbell, A. H. Bouchez et al. "LGS AO Operations at W.M. Keck Observatory." Proc. SPIE 6270 (2006).
8. Le Mignant, D., M. A. van Dam, A. H. Bouchez et al. "LGS AO at W.M. Keck Observatory: routine operations and remaining challenges." Proc. SPIE 6272 (2006).
9. Lu, J. R., Ghez, A. M., Hornstein, S. D., Morris, M., Matthews, K., Thompson, D. J., and Becklin, E. E. "Galactic Center Youth: Orbits and Origins of the Young Stars in the Central Parsec." JPhCS 54 (2006): 279.
10. Macintosh, B., et al. "Extreme adaptive optics for the Thirty Meter Telescope." SPIE 6272 (2006): 20.
11. Macintosh, B. et al. "The Gemini Planet Imager." SPIE 6272 (2006): 18.
12. Macintosh, B. et al. "MEMS-based extreme adaptive optics for planet detection." SPIE 6113 (2006): 48.
13. Makidon, R. B., A. Sivaramakrishnan, R. Soummer, B. R. Oppenheimer, L. C. Roberts, J. R. Graham, and M. D. Perrin. "The Lyot Project: understanding the AEOS adaptive optics point-spread function." International Astronomical Union Colloquium 200: Direct Imaging of Exoplanets: Science and Techniques (2006): 603-606.
14. Marchis, F., M. Baek, J. Berthier, P. Descamps, D. Hestroffer, and F. Vachier. IAU Circular 8817, 1, S/2004(45)1, Mar. 2007.
15. Marchis, F., M. Baek, P. Descamps, J. Berthier, D. Hestroffer, F. Vachier, F. Colas, J. Lecacheux, V. Reddy, and F. Pino. CBET 836. 1, (617) Patroclus, Feb. 2007.
16. Marchis, F., M.H. Wong, J. Berthier, P. Descamps, D. Hestroffer, F. Vachier, D. Le Mignant, and I. de Pater. S/2006 (624) 1. IAU Circ. 8732 (2006): 1.
17. Rafelski, M., Ghez, A. M., Hornstein, S. D., Lu, J. R., and Morris, M. "Photometric Stellar Variability in the Galactic Center." JPhCS 54 (2006): 316.
18. Sivaramakrishnan, A., B.R. Oppenheimer, M.D. Perrin*, L.C. Roberts, R.B. Makidon, R. Soummer, A.P. Digby, L.W. Bradford, M.A. Skinner, N.H. Turner, and T.A. Ten Brummelaar "Scintillation and pupil illumination in adaptive optics coronagraphy."

International Astronomical Union Colloquium 200: Direct Imaging of Exoplanets: Science and Techniques (2006): 613-616.

19. Stolte, A. "The Arches cluster - evidence for a truncated MF in the GC?" JPhCS 54: 217
20. Zawadzki, Robert J., Yan Zhang, Steven M. Jones, Stacey S. Choi, Barry Cense, Diana Chen, Alfred R. Fuller, Donald T. Miller, Scot S. Olivier, and John S. Werner. "Application of adaptive optics: Optical coherence tomography for *in vivo* imaging of microscopic structures in the retina and optic nerve head." SPIE's 2007 International Symposium on Ophthalmic Technologies XVII. San Jose, CA. 20-25 January 2007.
21. Zawadzki, Robert J., Yan Zhang, Steven M. Jones, R. Daniel Ferguson, Stacey S. Choi, Barry Cense, Julia W. Evans, Diana Chen, Donald T. Miller, Scot S. Olivier, and John S. Werner, "Ultra-high-resolution adaptive optics – optical coherence tomography: Towards isotropic 3 m resolution for *in vivo* retinal imaging," SPIE's 2007 International Symposium on Coherence Domain Optical Methods and Optical Coherence Tomography in Biomedicine XI, San Jose, CA, January 20-25, 2007.
22. Zhang, Yan, Barry Cense, Ravi S. Jonnal, Weihua Gao, Steven M. Jones, Scot Olivier, and Donald T. Miller. "Volumetric imaging of inner retina with adaptive optics spectral-domain optical coherence tomography." SPIE's 2007 International Symposium on Ophthalmic Technologies XVII. San Jose, CA. 20-25 January 2007.

Year 8 Ph.D. Thesis

1. Poyneer, L. A., "Signal processing for high-precision wavefront control in Adaptive Optics", PhD dissertation University of California, Davis, 2007.

Year 8 Conference Presentations & Abstracts

1. Adamkovics, M., I. de Pater, M. Hartung, F. Eisenhauer, R. Genzel, and C.A. Griffith. "Titan's Bright Spots: Multi-band Spectroscopic Measurement of Surface Diversity and Hazes." AAS-DPS 38. #48.07 (2006).
2. Azucena, O.A., L. Johnson, and J. Kubby. "Design of a MEMS laser guide star pulse tracker." Photonics West, San Jose, California. 24-25 January 2007.
3. Cense, Barry. "Current state of polarization sensitive OCT system in Indiana." CfAO Fall Retreat. Yosemite, CA. 16-19 November 2006.
4. Cense, Barry, Yan Zhang, Ravi S. Jonnal, Weihua Gao, Donald T. Miller. "Evaluation of polarization sensitive imaging with adaptive optics and optical coherence tomography." Association of Research in Vision and Ophthalmology. Fort Lauderdale, FL. 6-10 May 2007.
5. Cense, Barry, Yan Zhang, Ravi S. Jonnal, Jungtae Rha, Weihua Gao, Mircea Mujat, B. Hyle Park, Johannes F. de Boer, and Donald T. Miller. "Polarization-sensitive ophthalmic imaging with adaptive optics spectral-domain optical coherence." Symposium on Ophthalmic Technologies XVII. San Jose, CA. 20-25 January 2007.
6. Clare, R.M., Marcos A. van Dam, and A. H. Bouchez. "Modeling low order aberrations in laser guide star adaptive optics systems." Optics Express 15 (2007): 4711-4725.
7. de Pater, I., C. Laver, F. Marchis, H. Roe, and B. Macintosh. "Spatially Resolved Measurements of SO Emission on Io, while Eclipsed by Jupiter." AAS-DPS 38, 30.05 (2006).

8. Fernandez, B. and J.A. Kubby. "Large stroke actuators for adaptive optics." CfAO Fall Retreat, Santa Cruz, CA, 16-19 November 2006.
9. Fitzgerald, M., Kalas, P., Graham, J. R., Duchêne, G., and Pinte, C. "High-Resolution Imaging and Modeling of Circumstellar Debris: Architectures of Planetary Systems." BAAS 209 (2006): 11001.
10. Gao, Weihua, Barry Cense, Yan Zhang, Ravi S. Jonnal, and Donald T. Miller. "Measurement of the Stiles-Crawford Effect Using Optical Coherence Tomography." Association of Research in Vision and Ophthalmology. Fort Lauderdale, FL. 6-10 May 2007.
11. Go, C., I. de Pater, M. Wong, S. Lockwood, Marcus, P., X. Asay-Davis, and S. Shetty. "Evolution Of The Oval Ba During 2004-2005." AAS-DPS 38 (2006) #11.02.
12. Ghez, Andrea. Presentations at Cool Stars 14. Pasadena, CA. November 2006.
13. Ghez, Andrea. Aaronson Public Lecture. Tucson, AZ. 23 February 2007.
14. Ghez, Andrea. UCLA Library Associates, "Food for Thought" Program. Los Angeles, CA. 5 April 2007.
15. Ghez, Andrea. Presentation at Multiplicity in Star Formation. Toronto, Canada. May 2007.
16. Graham, J. R., Kalas, P., and Matthews, B. "The Signature of Primordial Grain Growth in the Polarized Light of the AU Mic Debris Disk." BAAS 209 (2006): 130.
17. Hammel, H. B., M.L. Sitko, G.S. Orton, T. Geballe, D.K. Lynch, R.W. Russell, and I. de Pater. "Distribution of Ethane and Methane Emission on Neptune." BAAS 209 25 (2006): 17.
18. Jonnal, Ravi S., Jungtae Rha, Yan Zhang, Barry Cense, Weihua Gao, and Donald T. Miller. "Functional imaging of single cone photoreceptors using an adaptive optics flood illumination camera." Association of Research in Vision and Ophthalmology. Fort Lauderdale, FL. 6-10 May 2007.
19. Kumar, G., Stevenson, S. B., and Roorda, A. "Saccadic targeting variability revealed by high magnification retinal imaging." [Abstract] Journal of Vision 6(6):495, (2006): 495a. <http://journalofvision.org/6/6/495/>, doi:10.1167/6.6.495.
20. Laver, C., I. de Pater and F. Marchis. "Near-IR Spectral Datacube Mosaics of Io taken with Osiris in 2006." AAS-DPS 38 (2006): 64.02.
21. Marchis, Hektor F., J., Berthier, M.H., Wong, P., Descamps, D., Hestroffer, F. Colas, I. de Pater, and F. Vachier. "Search of Binary Jupiter-Trojan Asteroids with Laser Guide Star AO systems: a moon around 624." Pasadena, CA. October 2006.
22. Marchis, F., J., Berthier, M.H., Wong, P., Descamps, D., Hestroffer, F. Colas, I. de Pater, and F. Vachier. "Near-IR Spectral Datacube Mosaics of Io taken with OSIRIS in 2006." Pasadena, CA. AAS-DPS 38 (2006): 65.07.
23. Marchis, F., Baek, M., Berthier, J., Descamps, P., Hestroffer, D., Kaasalainen, M., and Vachier, F. "Large Adaptive Optics Survey of Asteroids (LAOSA): Size, Shape, and Occasionally Density via Multiplicity." Workshop on Spacecraft Reconnaissance of Asteroid and Comet Interiors. Santa Cruz, CA, 5-6 October 2006. LPI Contribution No. 1325 (2006): 57-58.
24. Marchis, F., J. Berthier, M.H. Wong, P. Descamps, D. Hestroffer, F. Colas, I. de Pater,

- and F. Vachier. "Search of Binary Jupiter-Trojan Asteroids with Laser Guide Star AO systems: a moon around 624 Hektor." BAAS 38 (2006): 65.07.
25. Martin, S., I. de Pater, J. Kloosterman, S. Gibbard, and H.B. Hammel. "Multi Wavelength imaging of Neptune at High Spatial Resolution." AAS-DPS 38, #11.34, 2006.
 26. Miller, Donald T. "Adaptive optics high resolution retinal imaging." Optical Society of America Annual Meeting. Rochester, NY. 9-12 October 2006 (invited).
 27. Miller, Donald T., Barry Cense, Yan Zhang, Weihua Gao, James Jiang, and Alex Cable. "Retinal imaging at 850 nm with swept source optical coherence tomography and adaptive optics." Association of Research in Vision and Ophthalmology. Fort Lauderdale, FL. 6-10 May 2007.
 28. Miller, Donald T. "Why AO and OCT?" Association of Research in Vision and Ophthalmology. Fort Lauderdale, FL. 6-10 May 2007.
 29. Pennington, D., J. Dawson, and A. Brown. "Compact fiber laser for 589 nm laser guide star generation." AMOS Technical Conference, Maui, Hawaii. 10-14 September 2006.
 30. Pennington, D. M. "Compact fiber laser system for 589 nm laser guide star generation." Invited Talk. 2006 OSA Annual Meeting. Rochester, NY. October 2006.
 31. Perrin, M. D., and Graham, J. R. "Mid-IR Observations of Herbig Ae and Be Stars." BAAS 209 (2006): 23807.
 32. Roorda, A., E.A. Rossi, Y. Zhang, S.B. Stevenson, D.W. Arathorn, C.R., Vogel, A. Parker, and Q. Yang. "Applications For Eye-Motion-Corrected Adaptive Optics Scanning Laser Ophthalmoscope Videos." Invest. Ophthalmol. Vis. Sci. 47 (2006): E-Abstract 1808.
 33. Sheehy, C., Vacca, W. D., and Graham, J. R. "Diffraction Limited Imaging of the Stellar Population of IC 10 with Laser Guide Star Adaptive Optics and the Hubble Space Telescope." BAAS 209 (2006): 16710.
 34. Showalter, M.R., J.J. Lissauer, and I. de Pater, "Outer Rings and Chaotic Orbits in the Uranian System." AAS-DPS 38. 08 (2006).
 35. Stevenson, S. B. "Eye movement recording and retinal image stabilization with high magnification retinal imaging." [Abstract]. Journal of Vision 6.13 (2006):39, 39a. <http://journalofvision.org/6/13/39/>, doi:10.1167/6.13.39
 36. Wallace, J.K., B. Macintosh, M. Shao, R. Bartos, Phil Dumont, B. M. Levine, S. Rao, R. Samuele, and J.C. Shelton. "An Interferometric Wave Front Sensor for Measuring Post-Coronagraph Errors on Large Optical Telescopes." Presented at the IEEE Aerospace Conference, Big Sky MT. Paper #12954. March 2007.
 37. Zhang, Yan, Barry Cense, Ravi S. Jonnal, Weihua Gao, and Donald T. Miller. "Speckle reduction in retina imaging with adaptive optics optical coherence tomography." Association of Research in Vision and Ophthalmology. Fort Lauderdale, FL. 6-10 May 2007.

VII.1c. Dissemination activities not included elsewhere in the report

1. CfAO Fall Retreat – 120 Attendees including Researchers, Education collaborators and industrial representatives held at Tenaya Lodge, Yosemite November 17th to 19th 2006
2. Wiberg, Don, Seminars on adaptive optics topics at : Yonsei University, Seoul, Korea; Seoul National University, Seoul, Korea; Ajou University, Suwan, Korea, and UCSC Baskin Engineering, Santa Cruz.
3. Ellerbroek, B., Periodic updates to an AO simulation code (CIBOLA) have been uploaded to the CfAO website.
4. Stevenson, S., Software developed for analyzing videos was shared with other CFAO Theme 4 (Vision) members in 2006 and is now in use at Doheny Retina Institute to correct for eye motion in videos collected there on patients.
5. The 2007 CfAO Spring Retreat was held primarily at UC Santa Cruz March 26th to 29th . The Vision Science section was held at UC Berkeley. The Retreat consisted of a series of workshops as follows. Approx. 30 people attended each workshop
 - a. Development/Akami Electro-Optics Curriculum March 23rd 2007
 - b. AO for Visual Psychophysics (at UC Berkeley) March 26th to 27st 2007
 - c. Quantitative Astronomical AO Science March 26th to 27st 2007
 - d. CfAO Internship Short Course Planning March 27th 2007
 - e. Professional Development Workshop Debrief March 28th 2007
 - f. Science for Next Generation Keck AO March 28th 2007
 - g. Laser Technology and Systems for Astronomy March 29th 2007
 - h. Point Spread Functions for High Contrast AO
6. June 11, 2007 Program Advisory Committee Meeting
7. July 9 – 13, 2007 Keck Next Generation Adaptive Optics Workshop
8. August 6 – 10, 2007 8th Annual Summer School on Adaptive Optics

VIII.2. Awards and Other Honors

	Recipient	Reason for Award	Award Name and Sponsor	Date	Award type
1	Williams, David	Outstanding Research in vision Science	Honorary Doctor of Science, The State University of New York, State College of Optometry (to be presented in June 2007)	June 2007	Scientific Award
	Williams, David		Friedenwald Award	May 2006	
	Williams, David		Bressler Prize, Jewish Guild for the Blind (to be presented in October 2007 in NYC	October 2007	Science Award
2	Ammons, Mark	Support Ph.D studies	Brachman fellowship	November 2006	Fellowship

	Recipient	Reason for Award	Award Name and Sponsor	Date	Award type
3	Marshall, Perrin	Post Doctoral Researcher	NSF Fellow	2006	Fellowship
4	Fitzgerald, Michael P.		NASA/Michelson Fellowship at LLNL	2007	Fellowship
5	Eisner, Josuah A.	Discover talented scientists and to support basic research at UC Berkeley	Adolph C. & Mary Sprague Miller Institute for Basic Research in Science	2006-2009	Fellowship
6	Soummer, Remi	Support Post-doctoral Research	American Museum of Natural History's (AMNH) Kalbfleisch Postdoctoral Prize Fellowship Invitation by the College de France to lecture the French Academy of Sciences	September 2006 to August 2008 2007	Post-doctoral Fellowship
7	Grieve, Kate	Science Excellence	2007 ARVO Travel Grant	May 2007	Science Related
8	Cense, Barry	Science Excellence	2007 ARVO Travel Grant	May 20007	Science Related
9	Rossi, Ethan	Science Excellence	Graduate Teaching Assistant Award	2007	Science Related

VIII.3 Undergraduate, M.S. and Ph.D. students

	Student Name	Degree(s)	Years to Degree(s)	Placement
1.	Barczys, Matthew	Ph.D.	6	
2.	Carroll, Joe		Post-doc Univ. of Rochester	Asst. Professor of Ophthalmology at Medical College of Wisconsin
3.	Chen, Li	Ph.D.		Advance Medical Optics Research, Santa Clara, CA
4.	Duchene, Gaspard	Ph.D.	postdoc	Permanent Astronomer position in Grenoble France
5.	Fitzgerald, Michael	Ph.D.	6	NASA/Michelson Fellowship at LLNL
6.	Glassman, Tiffany	Ph.D.		Postdoc at SPITZER Science Center
7.	Gray, Dan	Ph.D.	5	Senior Engineer at Optos in Scotland

	Student Name	Degree(s)	Years to Degree(s)	Placement
8.	Hornstein, Seth	Ph.D.	6	Adjunct Professor at the Univ. of Colorado, Boulder
9.	Martin, Joy	Ph.D.	6	Optometrist in Ft. Worth, TX
10.	McCabe, Caer	Ph.D.		NRC postdoc at JPL
11.	Melbourne, Jason	Ph.D.	6	Postdoc at Caltech
12.	Metevier, Anne	Ph.D. UCSC	Postdoc UCSC	Postdoc research and teaching position at Sonoma State University
13.	Perrin, Marshall	Ph.D.	6	NSF Fellow at UCLA
14.	Porter, Jason	Ph.D.	6	Assistant Professor at University of Houston
15.	Raghunandan, Avesh	OD/Ph.D.	5	Faculty member at Michigan College of Optometry
16.	Raschke, Lynne	Ph.D.	7	CfAO's Education Program
17.	Sheehy, Christopher	BS	4	PhD Student at University of Chicago.
18.	Sheinis, Andrew	Ph.D. UCSC	Postdoc UCSC	Assistant Professor at University of Wisconsin
19.	Tanner, Angelle	Ph.D.		Postdoc Jet Propulsion Laboratory

VIII.4a General outputs of knowledge transfer activities since the last reporting period

	Patent Name and Inventors/Authors	Number	Application Date	Receipt Date (leave empty if pending)
1	Rapid, automatic measurement of the eye's wave aberration. Williams, D.R., Vaughn, W., Singer, B., Hofer, H., Yoon, G-Y, Artal, P, Aragon, J.L., Prieto, P., Vargas, F.	U.S. Patent #6,199,986		March 13, 2001.
2	Wavefront sensor with off-axis illumination. Williams, D.R. and Yoon, G-Y.	U.S. Patent #6,264,328		July 24, 2001
3	Rapid, automatic measurement of the eye's wave aberration. Williams, D.R., Vaughn, W., Singer, B, Hofer, H. Yoon, G-Y	U.S. Patent #6,299,311		October 9, 2001.

	Patent Name and Inventors/Authors	Number	Application Date	Receipt Date (leave empty if pending)
4	Apparatus and method for improving vision and retinal imaging. Williams, D.R., Yoon, G.Y., Guirao, A.	U.S. Patent #6,338,559		January 15, 2002.
5	Determination of ocular refraction from wavefront aberration data & design of optimum customized correction. Williams, D.R., Guirao, A.	U.S. Patent #6,511,180	10/00	January 28, 2003
6	Method and Apparatus for Using Adaptive Optics in a Scanning Laser Ophthalmoscope. A. Roorda	6,890,076		May 10, 2005
7	Synthetic Guide Star Generation. S. A. Payne, R. H. Page, C. A. Ebbers, and R. J. Beach	U.S. Patent 6,704,311	4/ 2001	March 9, 2004
8	High power 938 nanometer fiber laser and amplifier. Dawson, J.; Beach, R.; Drobshoff, A; Liao, Z.; Pennington, D.; Payne, S.; Taylor, L.; Hackenberg, W.; Bonaccini, D.		Sept. 29, 2003 Note: Filing for European Patent rights in progress,	
9	Method and Apparatus for the Correction of Optical Signal Wave Front Distortion Using Adaptive Optics. Peter Kurczynski, J. A. Tyson	US Patent 6639710	11/2001	12/28/2003
10	Method and Apparatus for Improving both Lateral and Axial Resolution in Ophthalmoscopy. D. T. Miller, R. S. Jonnal, and J. Qu and Karen E. Thorn	(US)Attorney Docket No. 217,568 International <i>PCT/US03/18511</i>	6/12/2002 2003	
11	A PZT unimorph based, high stroke MEMS deformable mirror with continuous membrane and method of making the same. E. H. Yang	CIT.PAU.14.P CT	6/12/02	
12	Adaptive Optics Phoropter. Scot Olivier, Brian Bauman, Steve Jones, Don Gavel, Abdul Awwal, Stephen Eisenbies, Steven Haney		October 4, 2002	

	Patent Name and Inventors/Authors	Number	Application Date	Receipt Date (leave empty if pending)
13	Repeatable Mount for MEMS Mirror System. Stephen Eisenbies, Steven Haney,		October 4, 2002	
14	Actuator Apparatus and Method for Improved Deflection Characteristics, M. Helmbrecht, Clifford Knollenberg	10/705,213	November 2003	
14A	Method and Apparatus for an Actuator Having an Intermediate Frame, M. Helmbrecht, Clifford Knollenberg	11/097053 10/705,213 Continuance	April 2005	
14B	Electrode Shaping and Sizing for an Actuator System, M. Helmbrecht, Clifford Knollenberg	11/096395 10/705,213 Continuance	April 2005	
14C	Method and Apparatus for Fabricating an Actuator System Having Buried Interconnect Lines, M. Helmbrecht, Clifford Knollenberg	11/097599 10/705,213 Continuance	April 2005	
15	Deformable Mirror Method and Apparatus Including Bimorph Flexures and Integrated Drive M. Helmbrecht	10/703,391	November 2003	November 2005
15A	Method and Apparatus for an Actuator System with Integrated Control M. Helmbrecht	11/097,777 10/703,391 Continuance	April 2005	
16	Method and Apparatus for Fabricating an Actuator System. Michael Helmbrecht	11/096,367	April 2005	
17	Application of map-seeking algorithm to determine motion estimation, image dewarping and stabilization. David Arathorn	Utility		
18	Algorithm for automated cone counting. David Arathorn	Provisional		

Table VIII.4a Continued

	License Name	Number	Licensed By	Date
1	“Method and Design for Using Adaptive Optics in a Scanning Laser Ophthalmoscope”	US Patent #6,890,076	Optos, Inc	10/2006
	Name of Start-Up Company	Main Product(s)		
1	Iris AO	MEMS Segmented Deformable Mirrors, AO controllers, AO development systems, AO imaging systems		

VIII.4b. Other outputs of knowledge transfer activities made during the reporting period not listed above.

An AO demonstrator was built at UC Santa Cruz and delivered to Maui Community College in Year 7. In Year 8, James Ah Heong, a University of Hawaii Hilo student, spent 3 months at the CfAO and the Laboratory for Adaptive Optics, building and commissioning an AO demonstrator. The demonstrator was destined for the electronics technology department at the Hawaii Community College, where it will be used as a teaching tool.

VIII.5 Center’s Partners

	Organization Name	Organization Type*	Address	Contact Name	Type of Partner**	>160 hours
1	Maui Economic Development Board (MEDB)	Non-profit	1305 North Holopono Street, Suite 1 Kihei, Hawaii 96753	Leslie Wilkins or Jeanne Skog	Education/Diversity	Y
2	Air Force Maui Optical and Super-computing Site (AMOS)	Military	590 Lipoa Parkway, Suite 103 Kihei, Hawaii 96753	Joe Janni	Education	N
3	Maui Com. College	Academic	310 Kaahumanu Kahului, HI 96732	Mark Hoffman or John Pye	Education/Diversity	Y
4	Hartnell Com. College	Academic	156 Homestead Ave Salinas, Ca 93901	Andy Newton	Education/Diversity	Y
5	Boeing – Maui	Company	535 Lipoa Pkwy, Suite 200 Kihei, Maui, HI 96753	Lewis Roberts	Education/Research	N
6	Oceanit - Maui	Company	MRTC, Suite 264 590 Lipoa Parkway Kihei, Maui, HI 96753	Curt Leonard	Education	N
7	Akimeka - Maui	Company	Akimeka, LLC 1305 N. Holopono St., Suite 3 Kihei, Hawaii 96753	Andrew Vliet, Cynthia Fox	Education	N
8	Trex - Maui	Company	MRTC, Suite 222 590 Lipoa Parkway	Allen Hunter	Education	N

	Organization Name	Organization Type*	Address	Contact Name	Type of Partner**	>160 hours
			Kihei, Maui, HI 96753			
9	Maui High Perform. Comp. Center (MHPCC)	Government	550 Lipoa Parkway Kihei, Maui, HI 96753	Gene Bal	Education	N
10	Institute for Astronomy	Academic	PO Box 0209 Kula, HI 96790	Mike Maberry	Education	N
11	Textron - Maui	Company	535 Lipoa Parkway, Suite 149 Kihei, HI 96753	Michael Reilly	Education	N
12	Smithsonian Submillimeter Array (SMA)	Observatory	645 North A'ohoku Place Hilo, Hawaii 96720	Billie Chitwood	Education	N
13	Exploratorium	Science Center	3601 Lyon Street San Francisco, CA 94123	Barry Kluger-Bell	Education	Y
14	W. M. Keck Observatory	Observatory	65-1120 Mamalahoa Hwy Kamuela, HI 96743	Sarah Anderson	Education/Research	Y
15	Gemini Observatory	Observatory	670 N. A'ohoku Place Hilo, Hawaii, 96720	Peter Michaud	Education/Research	N
16	Hispanic Associate for Colleges and Universities (HACU)	Not Profit	8415 Datapoint Drive, Suite 400 San Antonio, TX 78229	Tony Leiva	Education/Diversity	N
17	University of Hawaii – Hilo	Academic	200 W. Kawili St. Hilo, HI 96720-4091	Richard Crowe or Robert Fox	Education/Diversity	N
18	Pajaro Valley High School	Academic	500 Harkins Slough Rd Watsonville, CA 95076	Gary Martindale	Education/Diversity	N
19	Center for Informal Learning and Schools (CILS)	Academic	3601 Lyon Street San Francisco, CA 94123	Candice Brown	Education	Y
20	ALU LIKE	Non profit	458 Keawe Street Honolulu, HI 96813	Doug Knight	Education/Diversity	N
21	Institute for Astron. - Maui	Academic	4761 Lower Kula Road P.O. Box 209	Jeff Kuhn or Stuart Jefferies	Education	N
22	Institute for Astron. - Hilo	Academic	640 N Aohoku Pl # 209 Hilo, HI 96720	Darryl Wantanabe	Education	N
23	Educational Partnership Center	Academic	U.C. Santa Cruz 3004 Mission Street, Suite 220 Santa Cruz, CA 95060	Carrol Moran	Education/Diversity	Y
24	Carl Zeiss-Meditec	Company	5160 Hacienda Dve. Dublin, CA 94568	Barry Kavoussi	Research	Y
25	Northrop Grumman - Maui	Corporation	P.O. Box 398 Makawao, HI 96768	Albert Esquibel	Education	N

	Organization Name	Organization Type*	Address	Contact Name	Type of Partner**	>160 hours
26	Lucent Technologies	Company	Bell Labs. Murray Hill N.J	David Bishop	R & D	Y
27	Agile Optics	Company	1717 Louisiana, Suite 202 NE Albuquerque NM 87110	Dennis Mansell	R & D	N
28	Ciba Vision Corporation	Vision Company	11460 Johns Creek Parkway Duluth Georgia 30097		R & D	N
29	Lockheed Martin	Laser Division	135 South Taylor Ave. Louisville, CO 80027	Tim Carrig	R & D	Y
30	Wavefront Sciences	Company	14810 Central Ave, Albuquerque NM 87123	Tim Turner	R & D	N
31	Bausch & Lomb	Company	One Bausch & Lomb Place Rochester NY 14603	Peter Cox	R & D	Y
33	Lockheed ATC	Company	Palo Alto CA	John Breakwell	R & D	Y
34	Pacific Disaster Center	Agency	1305 North Holocono Street, Suite 2, Kihei, Hawaii 96753	Sharon Mielbrecht	Education	N
35	Subaru Telescope	Observatory	650 N. Aohoku Place Hilo, Hawaii 96720	Catherine Ishida	Education	Y

VIII.7 Summary Table

1	the number of participating institutions (all academic institutions that participate in activities at the Center)	11
2	the number of institutional partners (total number of non-academic participants, including industry, states, and other federal agencies, at the Center)	35
3	the total leveraged support for the current year (sum of funding for the Center from all sources <i>other</i> than NSF-STC) [Leveraged funding should include both cash and in-kind support that are related to Center activities, but not funds awarded to individual PIs.]	0
4	the number of participants (total number of people who utilize center facilities; not just persons directly supported by NSF) .	279

VIII.8. Describe any media publicity the Center received in the reporting period.

CfAO Research on the Web & Planetarium and Other Activities at UCLA

We have begun to develop a web-site to make our research available to the general community, including an overview of the Galactic Center (see proposal for next year's EHR work); the web effort is led by Jessica Lu and the animations have been downloaded by a large number of people from us to be presented in talks and the classroom. Seth Hornstein has invested a large amount of time in developing and running planetarium shows at UCLA. Tuan Do has taken over organizing planetarium shows and public telescope viewings at UCLA. We have also developed a planetarium show on the Galactic Center and are in the process of posting classroom problems on our website. S. Hornstein & M. Barczys (another CfAO supported graduate student) have also developed a planetarium show on Adaptive Optics.

Press releases:

Fall 2006 Issue of Keck Observatory Advancement Magazine: "Inspiring the Imagination"

(http://keckobservatory.org/support/magazine/2006/sept/06sept_5.htm)

West Hawaii Today, January 10, 2007: "Observatories offer summer internships - Akamai Program puts student astronomers on Mauna Kea"

Hamakua Times, January 2007 Issue: "Summer Internships Available at Hawaii Island Observatories"

Waimea Gazette February 2007: "Summer Internships Available at Hawaii Island Observatories" (same release)

UHH student in Santa Cruz to build adaptive optics teaching tool

Hawaii Tribune Herald -Wednesday, April 25, 2007

CfAO Research in Documentaries/Interviews

Andrea Ghez

Interview May 3 2007 for upcoming show "The Universe" on the History Channel

IX. Indirect/Other Impacts

IX.1 International activities

Center researchers have been active on the Organizing Committees and as speakers at international conferences. Amongst the most recent are:

The 6th International Workshop on “Adaptive Optics for Industry and Medicine” (June 12th – 15th. Galway, Ireland)

Astronomy with Laser Guide Star Adaptive Optics (Oct 29 - Nov 2, 2007, Ringberg Castle, Germany)

IX.2 Other outputs, impacts, or influences related to the Center’s progress and achievement

None to report

X Budget

Budget provided to NSF

X.4 Center Support from All Sources.

Award Source	Current Award Year		Requested Award Year	
	Cash (\$)	In-kind	Cash (\$)	In-kind
NSF-STC Core funds	4,000,000		3,320,000	
Other NSF			\$133,000	
Other Federal Agencies			\$125,000	
State Government				
Local Government				
Industry				
University				
International				
Private Foundations				
Other				
TOTAL	\$4,000,000		3,578,000	\$1,800,000

X.5 Breakdown of Other NSF Funding.

Funding Source	Current Award Year		Requested Award Year	
	Cash (\$)	In-kind	Cash (\$)	In-kind
STC underrepresented groups supplemental funds				
STC international supplemental funds				
NSF Directorate/Office Specify MPS/AST			\$133,000	
TOTAL				

X.6 Cost sharing

	Cash (\$)	In-kind
Annual	801,385	1,943,812
Cumulative (to date)	2,290,589	5,641,949

Signature C. W. P. Hart Date August 1 2007

Title Managing Director CfAO

See Y8 Cost Share Breakdown on Next Page

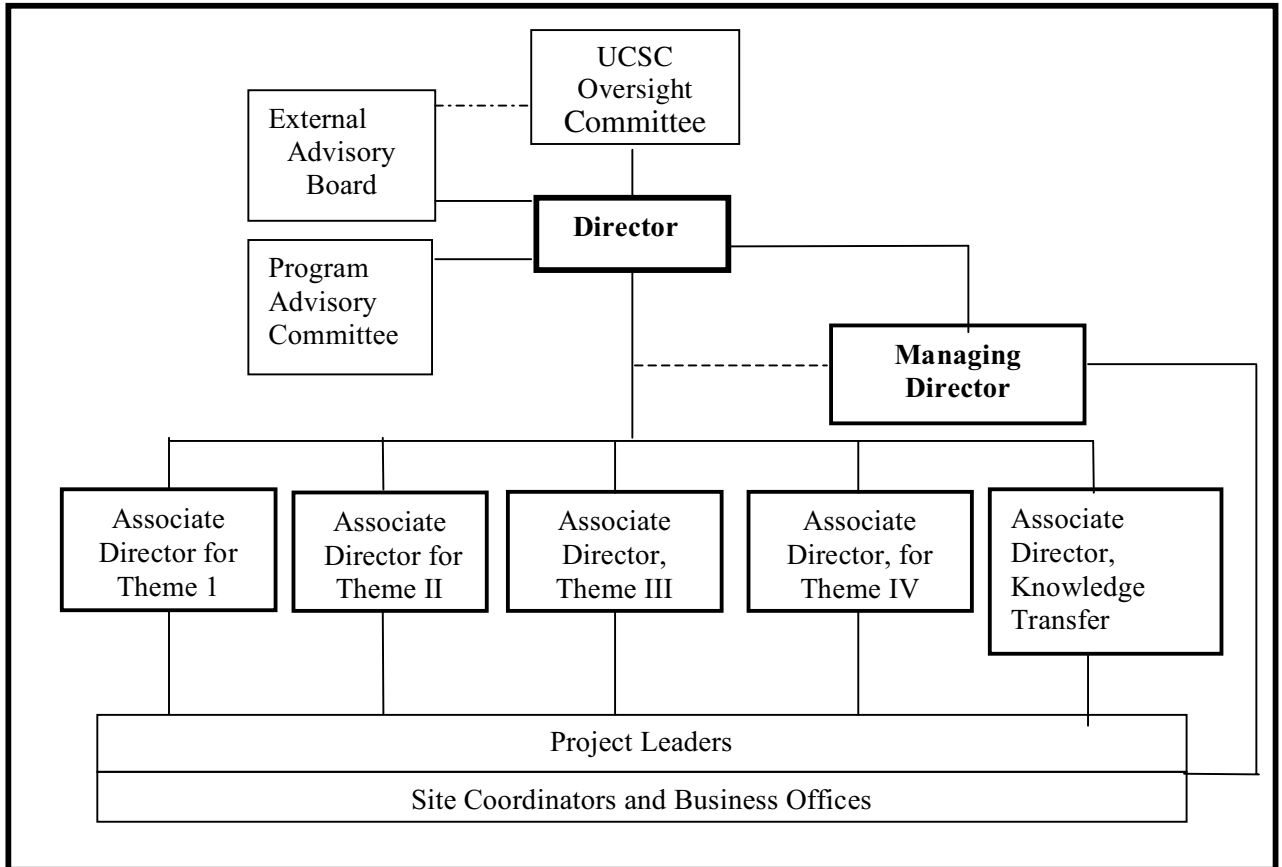
X.7 Additional PI Support from All Sources.

Award Source	Current Award Year		Requested Award Year	
	Cash (\$)	In-kind	Cash (\$)	In-kind
NSF	\$1,082,271		\$1,351,132	
Other Federal Agencies	\$2,963,748		\$3,102,796	
State Government				
Local Government				
Industry	\$96,000			
University	\$87,803	\$338,257		\$309,973
International	\$9,000			
Private Foundations	\$956,221			
Other				
TOTAL	\$5,195,043	\$338,257	\$4,453,928	\$309,973

Appendix A. – Biographical Information on New Faculty

There were no new faculty starting with the Center in Year 8.

Appendix B – Center Organizational Chart



Appendix C – External Reviewer Reports

Report of the External Advisory Board Meeting

Held 19 November 2006
Tenaya Lodge, Fish Camp, CA

Introduction

The External Advisory Board met during the annual CfAO retreat held from November 16-19, 2006 at Tenaya Lodge, Fish Camp CA. EAB meetings at the Retreat follows a recent trend to interact with all communities served by the Center and to meet and discuss progress, accomplishments, and plans with Theme leaders and Center performers. First-hand experiences gained at the Retreat have proved very useful to EAB members in formulating assessments and advice for out-year planning.

The members of the EAB are Bob Fugate (new chair as of Nov 6, 2006), NM Tech, Ray Applegate, U of Houston, Norbert Hubin, ESO, David Burgess, Boston College, Fiona Goodchild, UC Santa Barbara, Tom Cornsweet, Visual Pathways Inc. AZ, and Christopher Dainty, National University of Ireland, Galway. Ray Applegate, Fiona Goodchild, and Tom Cornsweet were unable to attend the meeting.

The External Advisory Board reports to the Vice Chancellor of Research at UC Santa Cruz, Bruce Margon. The EAB is charged with reviewing the policies, priorities and management effectiveness of the Center.

The primary focus of this EAB meeting was to listen to reports from theme leaders and to discuss and understand current thinking for CfAO's way ahead.

Report Summary

The presentations, discussions, and attendance at this fall retreat provided clear evidence that CfAO continues to produce excellent science, technology development, and outstanding support to the education of new scientists and engineers, especially in disciplines needed for adaptive optics.

Furthermore, the EAB finds that the CfAO leadership is thoroughly engaged in the execution and refinement of strategic plans to provide for continued funding of current initiatives in education and research themes. Theme leaders, in particular, have implemented the top recommendations from last year's strategic planning activities to develop plans that carry important research and education into the future beyond CfAO with potential funding sources identified. It is highly commendable that CfAO has stepped up to the task of planning for a transition so early. It would not be unusual for many organizations to wait until the last year, but CfAO has a 2.5 year head start. However, the Center's future role as a catalyst for the AO communities of astronomy and vision science is less clear.

CfAO's workshops, retreats, and conferences have become widely accepted as providing a unique opportunity for in-depth, widely diverse interactions between academic and industrial researchers, scientists, medical professionals, students, and administrators. The "centerness" of the AO community is that element of CfAO's mission most at risk beyond year 10 (more discussion below).

Prior to the meeting at Yosemite, CfAO's Managing Director suggested a topic for consideration by the EAB was how to optimize allocation of resources for years 9 and 10; consideration of focusing more resources on a few topics versus maintaining some support to a broader range of topics – a rifle or a shotgun. While we have some additional comments and a recommendation on this question below, the EAB feels that such choices should be in the hands of the Center Executive and Theme Leaders as a whole using the goals of a new strategic plan as a guidelines to set priorities. The cooperation shown between themes and the value of the education programs to 'glue together' all aspects of the research is the key enabler for successfully implementing this process. The CfAO working as a team can make the most intelligent decisions for the most benefit to CfAO and the AO community.

The EAB also strongly urges the UCSC administration to allow use of the current CfAO campus building for the transition activities of CfAO. Based on the plans developed to date it is evident to the EAB that there will be significant, vigorous adaptive optics research program centered at UCSC to support as a minimum astronomy and education related activities.

External Advisory Board Meeting

The EAB heard verbal reports from Claire Max, CfAO Director, Lisa Hunter, Education and Outreach theme leader, Bruce Macintosh, ExAO theme leader, Don Gavel, AO for ELTs theme leader, and Dave Williams and Scott Olivier, Vision Science leaders. Others present included Jerry Nelson, Chris Le Maistre, and Austin Roorda.

Director's Remarks

Clarie Max provided a situational awareness type summary or "State of the Center" overview. In general the educational component and core research efforts in themes 2, 3, and 4 are in reasonable shape for years 9, 10 and beyond with funding by sponsors either guaranteed or highly likely for the investigators now conducting work under CfAO funding (more under each theme discussion below).

It was clear that the Director is working hard on what she considers *not* to be covered by any current plan, the "centerness" aspects of CfAO – the networking, sharing, interactions, and diversity that has developed from retreats, workshops, summer schools, and conferences sponsored by CfAO. Approximately \$400K per year minimum is needed to maintain these activities assuming there is some change in the structure in which participants with sponsors pay their own expenses. Among her top candidates for funding sources is the University of California system and in particular the Multi-Campus Research Unit (MRU) program. CfAO is participating in a proposal for UC system-wide funding as part of the Institute of Geophysics and Planetary Physics (an existing MRU), where \$250K/year is being requested in support of ongoing CfAO "center" activities.

The NSF site visit team suggested hiring a full time fund raising development officer. There are several issues with this including making such a person productive in time and finding a legitimate source of funds for his/her salary. Claire Max thinks this concept may fit into a more general approach in which UC provides a development officer for three or more related groups including the UC Santa Cruz Astronomy Department, Lick Observatory, and CfAO. She will be vigorously pursuing this approach in early 2007.

Education

Lisa Hunter presented plans for two major pushes that have support external to CfAO. The first is an outgrowth of the successful Professional Development Workshop program. The new program is called the Institute for Scientist and Engineer Educators (ISEE), and its goals are to make scientists and engineers better educators. It will provide educational certificates for graduate students that go through the program. There is no money for this program yet, but its structure is mature, based on proven concepts developed under PDW (now called Professional Development Program, PDP), and has been introduced to the UC Administration which is showing support. At the fall retreat, significant progress was made on the organizational structure of the program, especially in relation to the university. The PDP is very successful with more applicants than positions this year (over 60 applied for 50 spaces).

The second major initiative is a continuation and expansion of the Hawaii education program. This program has a big push on Maui including transfer of coordination in the internship program from CfAO to Maui. Partners in Hawaii include Maui Community College, the University of Hawaii's Institute for Astronomy, the Maui Economic Development Board, and industrial partners. The Air Force Office of Scientific Research has pledged \$125K per year for five years and NSF is expected to contribute \$475K per year for five years under the new Akami Workforce Initiative program. One significant aspect of the new program is attention to mitigation of the cultural impact of astronomical facilities in Hawaii, in particular the NSF's Advanced Technology Solar Telescope slated for Haleakala on Maui. The program will address cultural impacts through community college classes, workforce development, and education of others on cultural practices and elements.

There was a short discussion of CfAO's de-emphasis of K-12 and the potential loss of the "catch them young" opportunity. Claire pointed out that NSF's objectives for STCs is to focus on people not well represented in the workforce. For CfAO this translates to support for bright minorities in community colleges and universities who have an interest in engineering but may not otherwise stay in engineering. This has been an effective use of CfAO resources for the present based on significant numbers of students and interns staying in engineering and especially adaptive optics.

Adaptive Optics for ELTs

Don Gavel reported on adaptive optics for Extremely Large Telescopes. Projects in this theme include support for technology development, primarily sodium wavelength lasers for guide stars, support of investigators making laser guidestar observations at Keck, performing AO modeling for ELTs, predictive control algorithms, MEMs based DMs and devices, and effects of sodium laser beacon spot elongation.

CfAO has made significant contributions to the development of AO algorithms that have been adopted in varying degrees for the baseline system of the Thirty Meter Telescope. However since TMT's baseline AO design is, according to Jerry Nelson, rather conservative (it does not employ MEMs based DMs for instance) CfAO doesn't receive any funding from TMT for advanced technology development. However, the positive aspect of this is that TMT did fund the CfAO affiliated Laboratory for Adaptive Optics for two conceptual studies (and results from one study, even though too risky for TMT management, represents the number one science instrument requested by the TMT science committee).

Perhaps more significant is that Keck may now use CfAO's conceptual study as the basis of their Next Generation Adaptive Optics initiative and CfAO and the Laboratory for Adaptive Optics could be primary players in Keck's program. Such an approach fits a logical paradigm in which advanced technologies are prototyped and evaluated at Keck before being adopted by TMT.

Beyond years 9 and 10, select Theme 2 research topics in ELT AO related areas of tomography, MCAO, MOAO, and other advanced topics could be sustained by California based funding sources. CfAO support to astronomers is expected to revert to traditional sources.

Extreme Adaptive Optics

Bruce Macintosh summarized CfAO's funded efforts in extreme AO, primarily prototyping and risk reduction for the Gemini Planet Imager (GPI). GPI is scheduled to see first light by 2010, well beyond CfAO year 10. Construction of GPI is funded by Gemini and risk reduction in areas of implementing MEMs, the calibration interferometer, apodizing chronograph, and predictive-controller algorithms are being funded by CfAO. In addition, CfAO is funding science studies, which will be the basis for a proposed science survey program using GPI. As CfAO funding ramps down in the next 2 years, the science studies may be reduced. In particular, after year 10 (2009), there will of course be no science (or other) funding from CfAO. 2010 will be the crucial year for the GPI team to carry out preparatory observations and prepare its proposal to be the primary science users of GPI - currently there is no identified solution for filling that gap. Lack of supplemental science funding could jeopardize CfAO researchers' opportunity to be the principal users of GPI.

Vision Science

David Williams and Scott Olivier summarized activities and plans in the vision science theme. David Williams highlighted the fact that two ophthalmologists gave talks at this retreat championing the benefits of adaptive optics for new discoveries related to early disease detection. These results are significant in answering earlier criticisms in the community that there had been no clinical trials of AO based instruments. The vision science community associated with CfAO is very keen to see the traditional activities (workshops, retreats, meetings, summer school) continue. Moreover, vision science laboratories have benefited by going to CfAO as a resource of new students and graduates.

In terms of moving forward from CfAO in vision science, the current focus is on two Bioengineering Research Partnerships (BRP), which are an outgrowth of work at CfAO. One is AO scanning laser ophthalmoscopy (David Williams is PI), and the other is AO Optical Coherence Tomography (Jack Werner of UC Davis is PI and Scot Olivier and Don Miller are members of this BRP).

A common goal in applying AO to vision science, supported by these two BRPs, is the development of a capability to image individual cells, especially in 3 dimensions, and watch their behavior as early indicators of disease. David Williams discussed the Cell Imaging Center concept being proposed at the University of Rochester. This Center has a broader scope than the work being done at CfAO both in types of cells and the technologies applied, however, the vision science aspects could easily fit in as a sub-center. There are a wide variety of possible funding sources including a NSF STC, as part of the National Institute of Health's roadmap plan, industrial partners (Optos, BMC, Bauch and Lomb, Merk, and others) and a combination of university sponsors.

Knowledge Transfer

Scot Olivier mentioned that a long awaited announcement from NSF for Engineering Research Center (ERC) proposals is now out (pre proposals due in May with final proposals due in a year) and that significant planning has gone into this already. This is not being viewed as an extension

of CfAO but entirely new and different with emphasis on cellular imaging. CfAO participants would most likely team with Boston University, Stanford, UCSC, and others. Current thinking is that Tom Bifano will serve as the PI for the ERC proposal.

Recommendations

The EAB feels the meeting was very productive makes the following recommendations.

1. The CfAO leadership (Center Executive and Theme Leaders) should develop internally a new, revised strategy that sets forth engineering, science, and education prioritized goals for years 9 and 10 plus expectations for those CfAO sponsored projects which could transition into new programs with future independent funding that carries beyond CfAO.
2. Rather than allocate fixed ratios by theme, the EAB recommends that investments in new proposals for years 9 and 10 be considered in the overall context of the new strategic plan. Requests for proposals should still be by theme, but this approach requires theme leaders to work cooperatively, to make intelligent decisions that are best for CfAO and AO in general, and to basically “do the right thing.” There is ample evidence that the current environment amongst theme leaders and CfAO management should make such an approach easy to implement.
3. Proposals funded during years 9 and 10 should strongly support the goals of the new strategic plan and should include a detailed transition plan showing potential sources of out-year funding if required.
4. The CfAO should be very open and widely publicize its new strategic plan to the AO community. It is better to inform participants as early as possible about technical goals, areas of priority, plans for education, and perceptions about those activities (retreats, summer school, workshops) initiated and normally sponsored by CfAO, which will be continued (or not).
5. Future retreats. The EAB recommends more plenary sessions for the remaining retreats. More plenary sessions could be achieved by adding a day to the normal schedule. In fact for the last retreat it is recommended that the entire meeting be plenary sessions. This would serve as a celebration of a decade of CfAO accomplishments.

Respectfully submitted 31 January 2007 by The External Advisory Board

Dr. Robert Q. Fugate, NM Institute of Mining and Technology, Chairman

Dr. Ray Applegate, University of Houston

Dr. David R. Burgess, Boston College

Dr. Thomas Cornsweat, Visual Pathways, Inc.

Dr. Christopher Dainty, National University of Ireland

Dr. Fiona Goodchild, UC Santa Barbara

Dr. Norbert Hubin, European Southern Observatory

b. The Program Advisory Committee

Program Advisory Committee Report for 2007

The Program Advisory Committee met June 11, 2007 with members of the CfAO executive committee. The main purpose of this PAC meeting is to provide advice on the handling of the Year 9 proposals. We also offer suggestions for the next two years of activities. This report summarizes the PAC conclusions. Present were:

PAC: Mark Colavita, Stanley Klein (chair), Carrol Moran, Malcolm Northcott and Rod Ogawa.
CfAO: Claire Max, Chris Le Maistre, Lisa Hunter, Austin Roorda, Don Gavel, Scott Severson & Bruce Macintosh.

The meeting began with Claire Max giving an overview of the past year, followed by detailed presentations of the four themes and the Summer School. Funding decisions of the Proposal Review Committee were discussed. The PAC supports those decisions with the exception that approximately \$150K should be obtained, either from the proposed budget for NSF funding or from other sources, to support efforts to plan for sustaining an active Center when NSF funds stop. It is likely that the way to support this planning is to hire a new person. That person could also be responsible for expanding dissemination of materials developed with NSF support. As we suggested last year we feel that for the next two years a significant portion of the budgets of the four themes be devoted to research projects that have a concrete plan for obtaining sustained post-NSF funding and sustained post-NSF community cohesion. In order for this to happen, careful thought should be placed on the calls for proposals for Year 10. We believe it is important that UCSC allow the Center to retain its building after NSF funding ends. It provides a physical nucleus for the community that CfAO members have said they value so highly. Without such a central facility, the community will assuredly collapse.

Theme 1.

The Education component of the CfAO has made substantial progress in the development of several effective models to accomplish its objectives. The creation of an innovative professional development component for graduate students to learn how to teach inquiry-based science has great potential for improving the future professoriate. Providing teaching venues for these graduate students has also supported another objective, to increase the number of students from under represented backgrounds entering undergraduate and graduate STEM programs. The COSMOS program for high school students, and the short courses and internships for undergraduate and community college students, all served the dual purpose of providing an opportunity for graduate students to practice their developing skills in inquiry based learning while preparing students from under represented backgrounds in the sciences to move forward in STEM academic pursuits. The success that CfAO has experienced at engaging community college students in pursuing higher education from the Hawaii partnership community colleges is another aspect that should not be lost. The great need to increase the participation of students from Hawaii in the future job market in Hawaii astronomy labs and to build better relationships between astronomers and Hawaiians is served well by this program. Because of its impact and the importance of this work the PAC recommends that more resources and attention should be focused during the last two years of the grant on planning efforts to sustain and disseminate the educational models developed through CfAO. This should be one of the tasks addressed by the new staff person we suggested hiring in the first paragraph of this report. We are encouraged by the direction to create the Institute for Scientist and Engineer Educators (ISEE), which will prepare science and engineering graduate students for their educational role as future faculty

members, and a wide range of other science and engineering careers requiring teaching skills. Graduate students will complete courses and gain practical teaching experience while completing their graduate studies through a flexible program that includes a certificate pathway. The PAC encourages the campus to provide financial support to ensure the continuation of these efforts by providing core infrastructure funding for the program. The PAC further encourages the Hawaii Partners to support the continuation of the professional development workshop in Hawaii.

Theme 2 The Theme 2 roadmap, and the shift in emphasis for the remaining years of the activity, is well thought out, factoring in both the past successes in this theme (in particular, LGS AO modeling), as well as the theme's desired legacy. The LGS science funded from Theme 2, such as CATS and the galactic center observations, will be one of the center legacies. The MEMS DM development has shown recent good results with the 1024 element mirror, with spin-offs including the GPI 4k DM consortium. In the laser area, it is satisfying to see Palomar LGS (which received several years of CfAO funding) working closed loop, and we note the two laser workshops held by the center to stimulate thinking on laser pulse formats (and other topics). The plan to incorporate the fiber laser project into VILLAGES provides a well-defined and trackable milestone for this activity. The new project on LGS PSF reconstruction is timely given the substantial LGS science on going. We note the substantial involvement of CfAO members in major ELT activities including the TMT telescope, AO, and instrumentation. We concur with the view for the future of Theme 2 to serve as a facilitator and to foster collaborations for the advancement of AO technology.

Theme 3 The PAC was pleased to see that the extreme AO project is well on the way to becoming an independently funded legacy of the CFAO. Funding of the adaptive optics planet finder by the Gemini telescope will bring the excellent research seeded by early CFAO funded work to the wider astronomy community. Once this instrument is successfully completed it will contribute significantly to our understanding of extra-solar planetary systems. As is often the case with new instrumental capability we can hope that this instrument will find interesting and unanticipated phenomena, in addition to completing the observations for which it is designed.

Theme 4. One of the main recent concerns of the PAC has been the issue of what happens after Year 10 of the Center grant. The Vision Theme has been active in that regard with resubmission of the 5 year Joint Bioengineering grant and plans for a new Center grant on retinal imaging. It was also gratifying that Don Miller's NIH proposal got excellent scores. It is not likely that these would have happened without CfAO. We were intrigued by the report of the Williams lab exploration of safe light levels in the process used to image ganglion cells. It sounded like the initial findings of possible light damage was handled very well and responsibly. That is an important finding and one hopes it will be followed up and publicized. CfAO has provided the vision community with a unique spirit of collaborative activity among several labs. One hopes that spirit can continue post CfAO funding. Maybe one or more large conferences or symposia, possibly in conjunction with the annual ARVO meeting, could be held in years 9 and or 10 to explore possibilities for maintaining the CfAO spirit in future years.

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

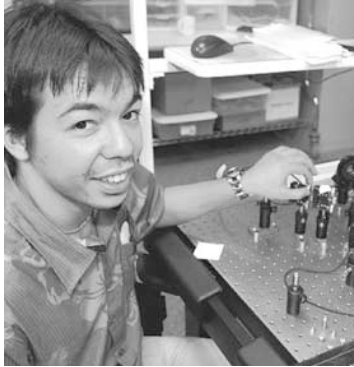


Appendix D: Media Publicity Materials

Press releases:

UHH student in Santa Cruz to build adaptive optics teaching tool

Hawaii Tribune Herald -Wednesday, April 25, 2007



James Ah Heong checks out the adaptive optics test bench at Maui Community College. The working tabletop adaptive optics system is used in the electro-optics curriculum. Ah Heong is in California for three months helping to assemble a similar bench for Hawaii Community College.- - Sarah Anderson/Keck Observatory