Center for Adaptive Optics

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# An Introduction to the AEOS Adaptive Optics System

Lewis C. Roberts, Jr.
The Boeing Company

The Advanced Electro-Optical System (AEOS) telescope became operational in the summer of 2000. It is the largest telescope at the Maui Space Surveillance System located at the summit of Haleakala on the island of Maui. Haleakala, at a height of 10,023 ft, has similar conditions to those on Mauna Kea. However even though it is shorter than Mauna Kea, it experiences more turbulence and higher levels of water vapor.

The main users of the AEOS telescope and sensors are the U.S. Air Force and other branches of the U.S. government interested in imaging satellites. However while it was primarily designed for this mission, it was also intended to be a dual use facility. In 2000, the Air Force Office of Scientific Research and the National Science Foundation teamed to offer the astronomy community access to the telescope.

One of the primary sensors of the 3.63-m AEOS telescope is an adaptive optics (AO) system, which unlike most other systems is designed to acquire images at visible wavelengths. With 941 actuators on the deformable mirror, it is one of the highest order AO systems currently in operation. As such, it offers an unprecedented opportunity to study high order AO performance under operating conditions. Sample images are shown in Figures 1-5. All objects served as their own guide star.

*NSF Science and Technology Center for Adaptive Optics*

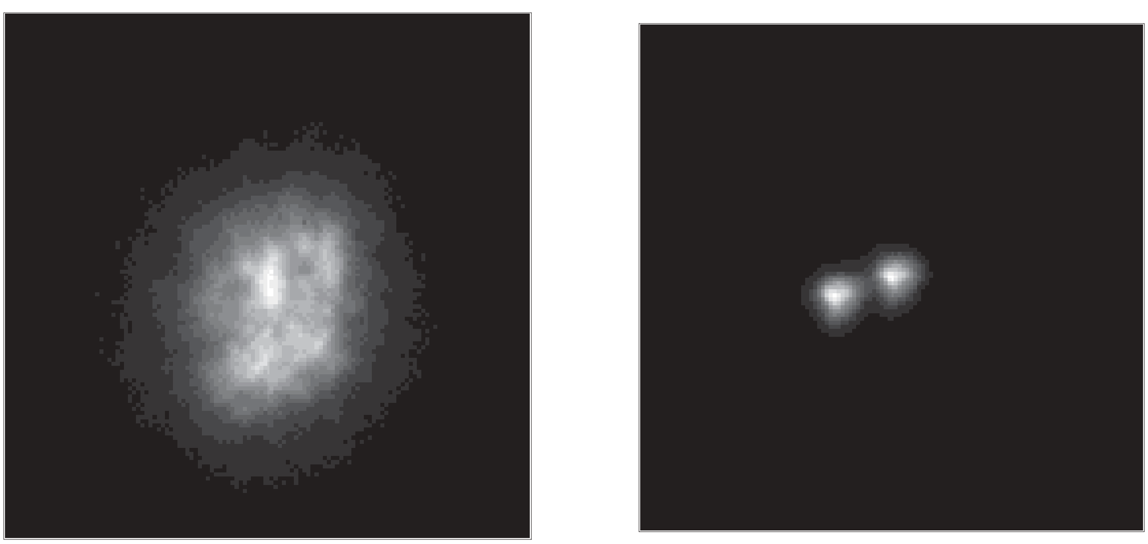

Figure 1. Above are two I-band images of the binary star STT 535 AB taken with the AEOS AO system on 2001 June 19. The left and right hand figures represent open and closed loop operation respectively. The binary star has a separation of 0.3 arcsec. The differential magnitude is 0.067.



*The National Science Foundation Science and Technology Center for Adaptive Optics, University of California, Santa Cruz, CA 95064*
*Phone: (831) 459 5592*
*Fax: (831) 459 5717*
*email: cfao@ucolick.org*

*Copies of Newsletter available on CfAO website:*
http://cfao.ucolick.org/pubs/newsletters.php

# The AEOS Adaptive Optics System (Continued)

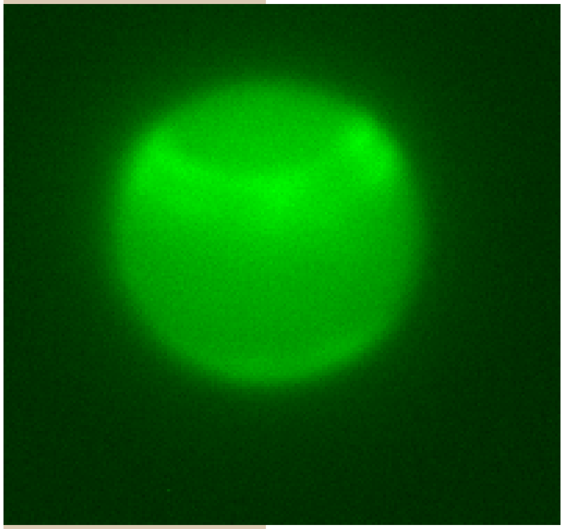

Figure 2. Neptune taken with the AO system on 2001 August 8 . It is an I-band image and clearly shows atmospheric structure. This is a portion of the 10" field of view of the science camera.

Figure 3. An I-band image of Uranus taken with the AO system in 2001 August 8.

Figure 4. The AO system can be used to study planets with large angular extents such as Mars, Mercury or Venus. This is an I-band image of Venus with the AO system on. The image quality is degraded as it was taken at 14 degrees above the horizon. The phase of Venus is easily seen. Venus has few if any surface features in the visible.

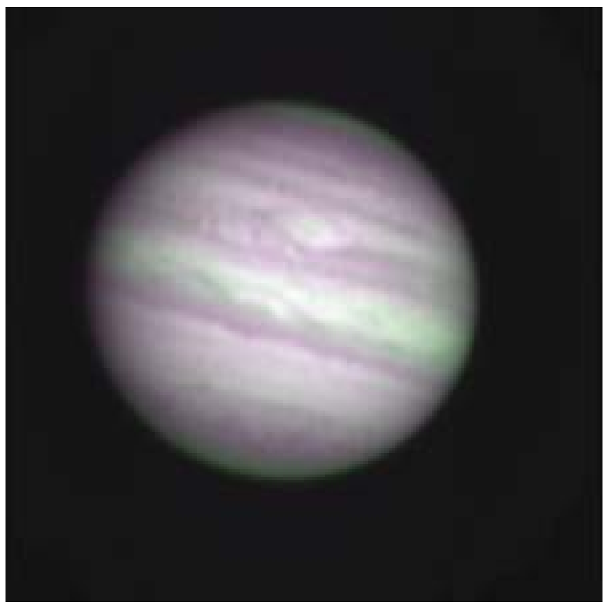

Figure 5. The AO system can not image objects bigger than about 9 arcseconds in diameter. The tip/tilt system still works on these objects. The above image is a false-color combination of two narrow band methane band filters using the tip/tilt system on Jupiter. The image was taken on 2003 March 14 using the wide field of view (60') on the science camera. The science camera is undersampled when using this field of view.

## Hardware Overview

The AO system is located three floors below the AEOS telescope in the central coude' room. The f/200 beam sent down by the telescope is intercepted by the AO pick off mirror. This directs the beam onto an optical bench that supports the main optical assembly consisting of the tip/tilt mirror, the deformable mirror (DM), and four multi-mirror pupil relays. Each pupil relay is a multi-mirror all reflective design. The first relay places a pupil image on the tip/tilt mirror and the second places a pupil image on the DM. After the third pupil relay, the optical beam is divided by wavelength and sent to different subsystems. In the standard configuration, the short wavelength light from (400 nm to 700 nm) is reflected to the wavefront sensor (WFS) and tip/tilt system. Light from 700 nm to 5 micron is sent to the science camera or to an experimental coude' suite. The science camera is a 512x512 12-bit CCD camera designed for high speed imaging. A 50/50 beam splitter can replace the dichroic and it sends white light to the visible Imager or a coude' suite, albeit at the cost of sending 50% less light to the WFS and tip/tilt system.

Seven coude' suites surround the central coude' room. These suites are extremely useful for visiting experimenters who bring their own science instruments. Rather than having to package the instrument for mounting on the side of a telescope, it can be spread across an optical bench, which makes AEOS an ideal place to test and prototype instruments. Several of the NSF/AFOSR supported experiments have made use of this capability and it is expected more will do so in the next round of proposals.

Due to the alt-az design of the telescope the beam entering the WFS CCD and tracker CCD rotates as the telescope tracks objects; additionally these cameras have no atmospheric dispersion correction (ADC) capabilities. The science camera does have its own internal ADC and image derotator, but if the beam bypasses it, no dispersion correction or image derotation is provided.

The AO system can reliably close loop on objects brighter than 8$^{th}$ magnitude. Closing loops on objects fainter than 8$^{th}$ magnitude is highly dependent on seeing and sky conditions. Objects as faint as V=9.5 have been closed on, though performance was subpar. For objects fainter than this, the tip/tilt system can be used by itself, which provides some image improvement. The tip/tilt system can also be used on large objects. The AO system has difficulty closing loops on objects larger than 9 arcseconds due to the lenslets on the WFS resolving the object.

More details of the AO system hardware and performance can be found in an article published in the November 2002 issue of the Publications of the Astronomical Society of the Pacific (Roberts & Neyman 2002).

### Experiments Using AEOS AO

As mentioned above, the NSF and AFOSR have teamed to provide access to the telescope to astronomers. So far two cycles of the proposal have been awarded and the third is expected out in early 2003. The program has concentrated on the AEOS AO system, but other site instruments are useable as well as visitor instruments.

A list of the projects follows as well as the principal investigator and their institution. Those focused on AO include a survey of OB-stars for faint companions (Theo ten Brummelaar Georgia State University), a survey of X-ray selected A-stars for faint companions (Jennifer Patience, Lawrence Livermore National Laboratory), monitoring of Titan's atmosphere (Michael Brown, California Institute of Technology), testing of a new AO imaging spectrograph (Keith Hege, University of Arizona), monitoring of Io and Europa's atmosphere (Michael

Mendillo, Boston University), design and construction of a coronagraph to detect extrasolar planets (Ben Oppenheimer, American Museum of Natural History), observations with an IR coronagraph (Scott Milster, Air Force Research Laboratory), imaging of Io's sodium cloud (Nick Schneider, University of Colorado), observation of the December 2001 Titan occulation (Eliot Young, Southwest Research Institute), observations of Jupiter and Saturn with an tunable filter photometer (Nancy Chanover, New Mexico State University), and monitoring of the atmospheres of Mars, Jupiter and Saturn (James Murphy, New Mexico State University). These projects cover a wide variety of objects. Some used the site's science camera, while other's brought equipment designed for their specific experiment.

The system is also used by staff members for internal research projects. These have included measurements of the astrometry of high dynamic range binary stars, computation of the orbit of the multiple star Iota Cassiopeiae, observations of Mercury to map out surface structures, images of the near-Earth asteroid 2002 NY40 to study its morphology and studies of atmospheric turbulence. While the AO system could not be used, the science camera was used to observe the 2002 August Pluto occultation and the 2003 March occultation by the asteroid Intermnia.

## Conclusion

*The AEOS AO system is one of the highest order systems in the world, as such it offers an unprecedented opportunity to gain experience with such a system. The lessons learned here can be applied to the next generation of high order AO systems on the giant telescopes (> 10 m) currently being planned. The system is not perfectly suited to astronomy, due to the 12-bit nature of the science camera and the relatively bright limiting magnitude, but, by carefully selecting targets, it can produce high quality science.*

# Pursuit of micron-resolution Imaging in the Eye

**Donald T. Miller, Ravi S. Jonnal, Karen E. Thorn, and Junle Qu**
*Indiana University School of Optometry, 800 East Atwater Ave, Bloomington, IN 47405 USA*
dtmiller@indiana.edu
http://www.opt.indiana.edu

## 1. Introduction

We have known for at least 150 years that the human eye contains many optical imperfections, i.e. aberrations. The most significant of these, defocus and astigmatism, are routinely corrected by spectacles and contact lenses. The remaining aberrations, although small in comparison, are still significant enough to be a major bottleneck for high-resolution retinal microscopy. When looking into the eye with a microscope, the uncorrected aberrations blur the view of the retina and prevent observation of microstructures the size of single cells. Because pathogenesis begins at the level of the cell, non-invasive observation of cells in the retina may lead to more precise and timely diagnosis and better informed treatment.

Despite this potential, the necessary technology did not historically exist to readily measure let alone to correct these additional aberrations in the eye. It was not until the 1990s when vision scientists took notice of the wonderful solutions that the astronomy and military communities had developed for taking the twinkle out of stars – namely adaptive optics (AO) - that these long standing technological barriers began to crumble. Perhaps the most catalytic of these was the first successful application of adaptive optics to the eye by Liang, Williams, and Miller in the mid-1990s that allowed observation of single retinal cells in living human eyes with normal optics. Today the use of adaptive optics in conjunction with a dilated pupil to minimize diffraction, routinely increases the transverse resolution by two to three times, corresponding to a blur size at the retina of two to three microns. This increase in resolution is significant as many cells in the retina are on the micron scale.

Given the differences between astronomical telescopes and retinal cameras, both in size and purpose, it is surprising that vision science and the eye care profession find astronomical technology useful. Nonetheless this was indeed the case for AO in which all major aspects of the AO system were borrowed. This juxtaposition was nicely captured this past spring by a cartoon that appeared in the Canberra Times (Australia) and is shown in Figure 1. Several CfAO members were quoted in the article.

Fig. 1. Cartoon illustrating the collaborative use of adaptive optics for astronomy and vision science. The cartoon accompanied the article, "Starlight, eyebright" that was published this past spring in the Canberra Times, Australia.

Interestingly, what the cartoon does not capture is that astronomical imaging is largely two-dimensional in nature (right ascension and declination), while retinal imaging is highly three-dimensional due to the addition of depth. This extra dimension stems from the tight packing of cells in distinct layers that are stacked on top of each other to form the thick retina (see histological cross section of the human retina in Figure 2). Reflections from these cellular layers are typically of low contrast and create a host of superimposed images at the detector. It is likely because of this jumble of images that only bright, high contrast cells have been visualized in the intact eye with current AO cameras. This corresponds to less than 0.2% of all the cells in the human retina. Separating these images requires optical sectioning of the retina and this implies an effective axial resolution that approaches the size of an individual cell. It is for this reason that the high transverse (two-dimensional) resolution that can be obtained with AO is by itself largely insufficient for imaging cells in the retina.

In light of this major problem, the Indiana group spearheaded the first effort to develop an AO retina camera that is designed to work with an extremely effective optical sectioning technique called optical coherence tomography (OCT). OCT is the optical analogy of ultrasound. The method relies on a Michelson interferometer employing a low temporal

## Micron-resolution Imaging in the Eye

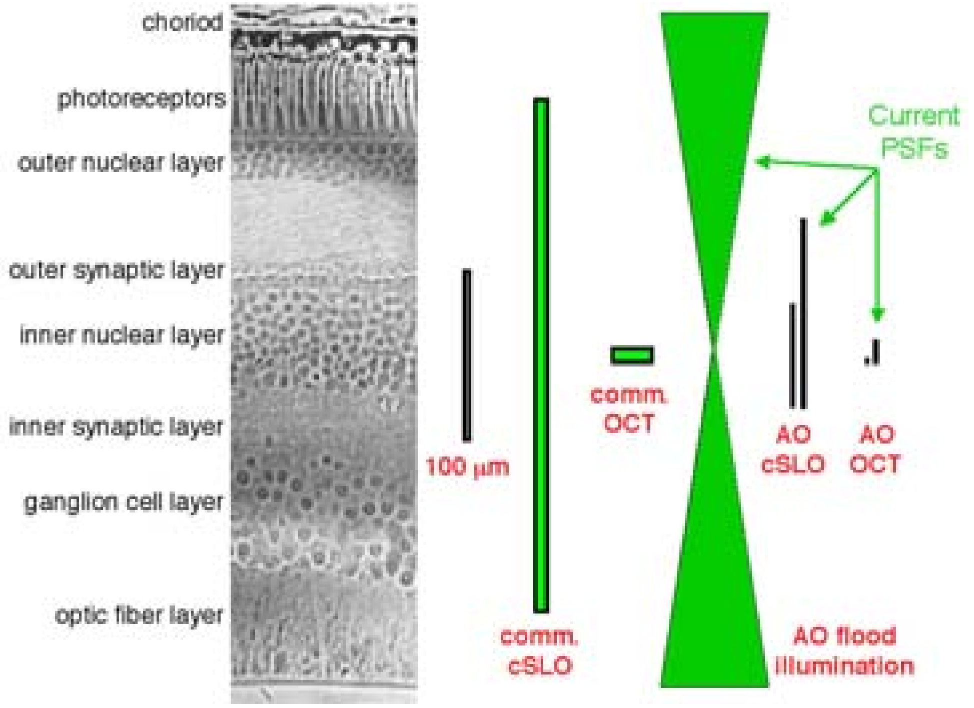


Fig. 2. Point spread functions (PSFs) drawn to scale for various combinations of AO and camera architectures (cSLO, OCT, and conventional flood-illumination). For simplicity the PSFs are displayed as 2-D projections with their width and height representing the camera's lateral and axial resolution, respectively. Full aberration correction is assumed across an 8 mm pupil. Wavelength is 0.85 microns. For comparison, a histological cross section of human retina at 4.17 deg ecc. and accompanying scale bar are shown on the left. Also note that the displayed PSF for the AO flood illuminated camera does not represent the true PSF, but rather an effective one that actually extends beyond the figure.

coherence light source that coherently filters light reflecting from the sample based on its time of flight. Axial movement of the coherent filter through the retina allows optical sections at different depths to be retrieved. OCT systems for the eye typically provide optical slices that are 10 to 20 microns thin. More recently, ultra-high resolution OCT systems have been developed with axial resolutions below 3 microns.

The high axial resolution of OCT complements the high transverse resolution of AO and together they provide a powerful imaging tool whose image quality can surpass either methodology alone. The significance of this combination is illustrated in Figure 2, which shows the 3D point spreads for the three major camera architectures with AO: conventional flood illumination[1,4,5] confocal scanning laser ophthalmoscope (cSLO)[6], and OCT[7]. The point spreads of two commercial instruments (without AO) are also displayed. Point spreads colored green indicate what has been achieved to date; black indicates the ultimate goal using current state-of-the-art technology. A scaled histological cross section of the human retina is shown on the left for comparison. Note the size of the point spreads relative to each other and to the retina cells. The two AO-OCT point spreads are noticeably smaller than those of the other cameras indicating a significantly higher resolution. The volume of the black AO-OCT point spread is 45 mm$^3$ and is 16,000 times smaller than the commercial cSLO. More importantly, the AO-OCT point spreads are at least as small as many of the cell nuclei shown in the retina cross section suggesting that these cells are resolvable in three dimen-

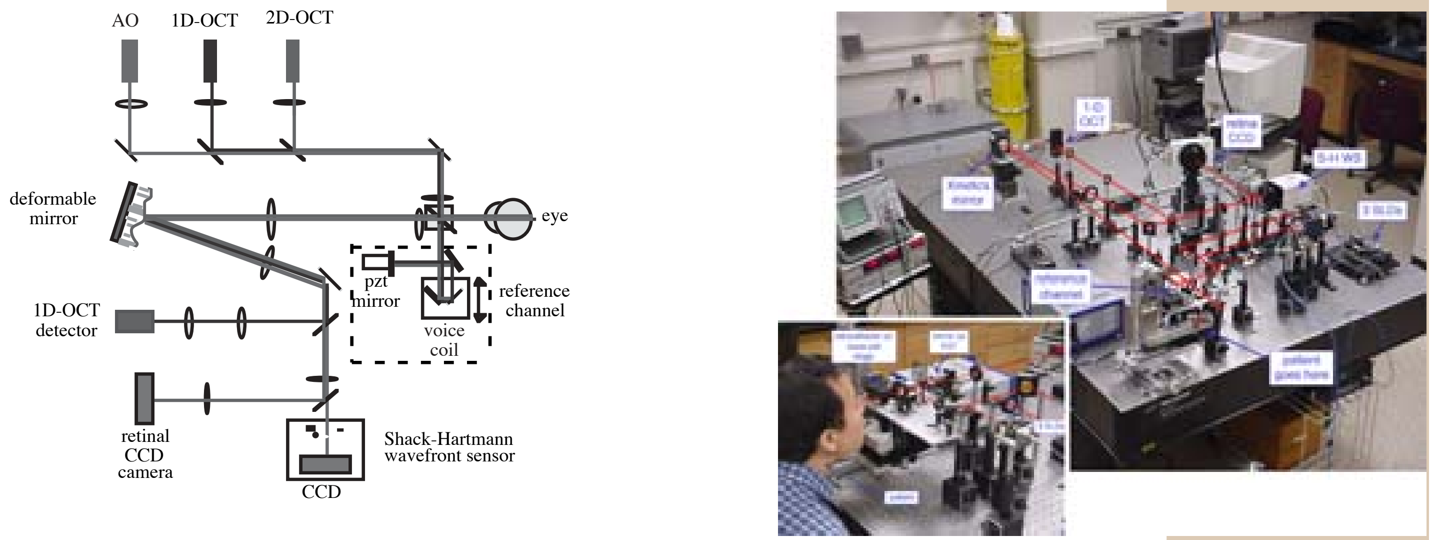


**Fig. 3.** Schematic (left) and photo (right) of the Indiana AO-OCT retina camera. It consists of an AO system for correcting ocular aberrations, 1-D OCT for axial retina tracking, and a flood-illuminated *en face* OCT system (CCD-based) for optical sectioning the retina. A separate light source is used for each task. Inset: Close-up photograph of Junle Qu whose eye is aligned to the camera using a xyz bite bar stage and accompanying optical platform that holds the reference channel of the OCT system.

sions and should be observed if there is sufficient signal to noise.

## 2. Indiana AO-OCT retina camera

A flood-illuminated en face (x-y) OCT scheme was chosen for the Indiana camera that acquires area images of the retina with a scientific-grade CCD. A major strength of parallel detection is its insensitivity to retinal motion blur as thousands of points can be collected simultaneously. An additional advantage is its compatibility with AO. A schematic and photo of the Indiana AO-OCT retina camera are shown in Figure 3. The camera consists of three independent yet highly synchronized sub-systems to perform (1) aberration compensation, (2) axial retina tracking, and (3) en face OCT imaging. Each is described below.

*Aberration compensation:* Compensation is realized with an AO system that employs a 37 actuator Xinetics mirror and a Shack-Hartmann wavefront sensor consisting of a 17x17 lenslet array that samples a 6.8 mm pupil at the eye. The closed-loop control operates at up to 22 wavefront corrections per second.

*Axial retina tracking:* Accurate optical sectioning of the retina requires compensation for involuntary axial motion of the patient's head and eye while aligned to the camera. This is accomplished with an infrared 1-D OCT that tracks the front of the retina at up to 20 Hz. Measurements on several subjects revealed a retina motion ranging from 7 to 30 microns RMS over 5 to 10 second intervals.

*En face OCT Imaging*: *En face* slices of the retina are obtained using a four-step phase shift reconstruction method, analogous to that employed in phase-shift interferometry. The system can capture four images in less than 7 msec to mitigate eye motion artifacts.

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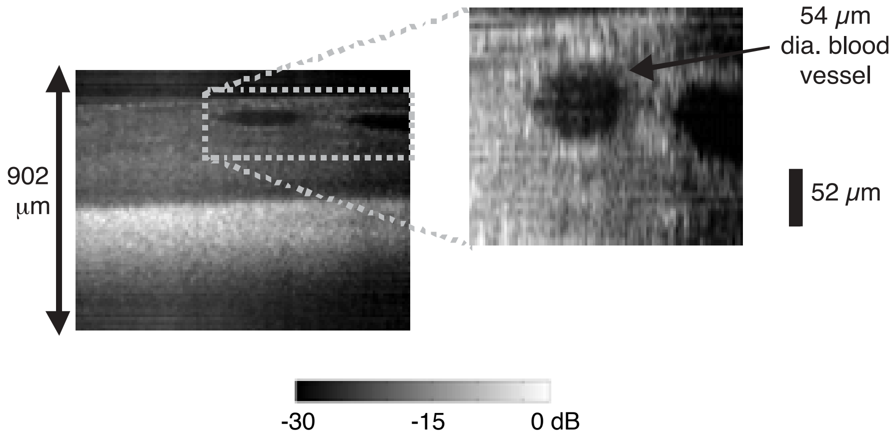



**Fig. 4.** (Left) Cross-sectional slice (x-z) through a stack of *en face* (x-y) OCT images of an *in vitro* bovine retina. (Right) A subsection of the x-z slice is displayed with the transverse and depth dimensions resized to the same linear scale.

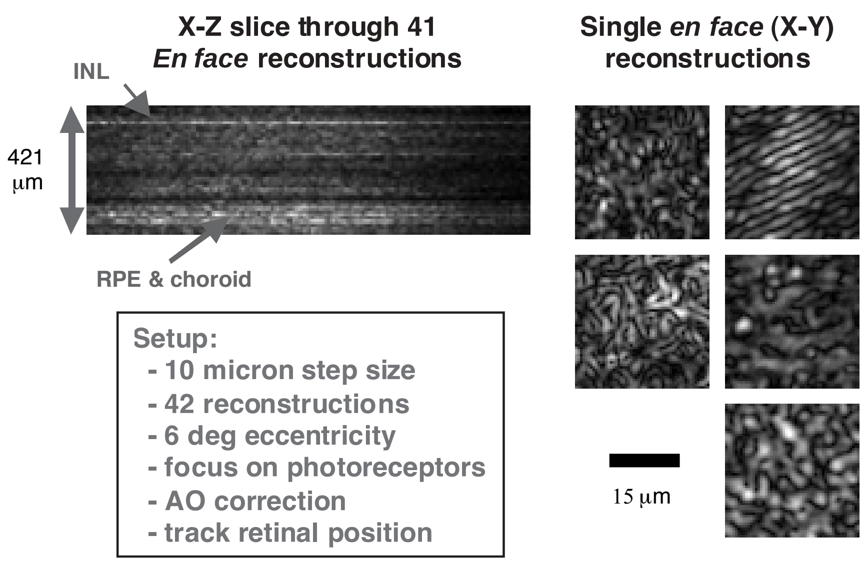



**Fig. 5.** (Left) Cross-sectional slice (x-z) through a stack of 41 *en face* (x-y) OCT images of the living human retina. (Right) Small sections of single *en face* OCT images are shown from different depths in the 3-D reconstruction.

### 3. Results with the Indiana camera

As a first step towards validation of the camera, images were collected on *in vitro* bovine and goldfish retina. Figure 4 shows a cross-sectional slice (x-z) through a stack of 200 *en face* (x-y) images obtained on a bovine retina. The dark region on top is saline solution, which reflects little light; the middle gray band is believed to be the retina; the dark oval structures lying immediately below the retinal surface are cross sections through small blood vessels; and the bright band deeper in the tissue is suggestive of the highly reflective retinal pigment epithelium layer and choroid. The bright band starts at 365 microns below the retinal surface. The rescaled image on the right reveals blood vessels (dark patches) that are circular as would be predicted by histology. Note the relatively sharp edges of the 54 micron diameter blood vessels that is indicative of the 14 micron axial resolution. The natural appearance of the images, such as the distinctively curved boundaries between the saline solution, retina, and RPE as well as the circular appearance of the vessels, provides supportive evidence that the camera is performing correctly.

Retina images were next collected on several subjects. Figure 5 shows a cross-sectional slice (x-z) through a stack of 41 *en face* OCT images obtained on one subject. The slice reveals bright reflections at what is likely the inner limiting membrane (retinal surface), retinal pigment epithelium, and choroid. The dynamic range in the image is about 25 dB and is sufficient for capturing *en face* images of several bright tissue layers. The right side of Figure 5 shows five small sections of *en face* images obtained from different depths in the volume data set. The resolution in these images peaks at 2.4 mm (transverse) by 14 mm (depth) yielding a voxel resolution that is 10 times smaller than the next best optical sectioning camera, the AO-cSLO (see Figure 2).

The combination of AO and OCT provides a major leap in resolution over competing camera architectures, but it is not without risk. AO and OCT are individually complex technologies and their combination is even more so. In addition, the interferometric nature of OCT relies on the coherence property of the illuminating light, and this coherence produces unwanted speckle noise that mottles the OCT image and confounds interpretation of image content. The *en face* images in Figure 5, for example, are indeed heavily contaminated with speckle. The average theoretical speckle size for our camera configuration is 1.9 microns. This is smaller than the cell features we want to observe. However, experimental results indicate that cellular identification is largely compromised by this speckle. We have also discovered that this level of speckle makes focusing in the retina very challenging. We are currently working on several solutions to these problems.

### 4. Conclusion

To our knowledge we have developed the first AO-OCT system of any kind in the world, made possible by the interdisciplinary nature and infrastructure of the CfAO. In the years to come the project will strategically position the Center as the adaptive optics catalyst and hub to which researchers and engineers of this rapidly growing field will turn to for advice in implementing AO in their own OCT systems, many with applications beyond imaging the eye.

We are currently soliciting industrial partners for Indiana's AO-OCT intellectual property and will expand our efforts in the AO-OCT arena through a newly awarded NEI-BRP grant that involves UC-Davis (headquarters) and LLNL. The group will develop and conduct vision science with two complementing AO-OCT retina cameras that employ novel scanning and flood illuminated approaches ■

# People and Profiles


Malika Moutawakki

*Malika Moutawakkil,* Malika recently completed her Master’s Degree in Chemistry at UCSC and joined the CfAO as Education Coordinator. Malika temporarily acted in this position in the summer of 2001. She is responsible for the Stars and Sight Summer COSMOS program for high school students and for the recruitment and placement of undergraduates in the CFAO run Research Experience for Undergraduates (REU) program.


Hilary O'Bryan

*Hilary O’Bryan*, Hilary recently completed a Bachelor’s degree in Bio-chemistry at UCSC. She has joined the CfAO staff in a part time Administrative assistant position. In her spare time she is studying towards a nursing diploma.


Nayhieli Cruz

*Nayhieli Cruz,* Nayhieli has worked as a part time Administrative Aid in the CfAO office since July 2000 and provided on-site administrative assistance at all the CfAO Retreats. Nayhieli completed her Bachelor’s degree in Business Administration at San Jose State in May 2003. She has been promoted and will be a Human Resources specialist for Lick Observatory.


Stephanie Avila

*Stephanie Avila* participated in the CfAO “Stars, Sight and Science” program for high school students in the summer of 2001. In her senior year in high school she worked on a science fair project entitled, “Stellar Nursery: A Study of the Wild Duck Cluster”, which she started during “Stars, Sight and Science”. The project won first place in its category in Monterey County and several other awards and can be seen at: http://www.redshift.com/~vikweb/WildDuck.html.
Stephanie has completed her freshman year at the University of California, Berkeley, where she is majoring in anthropology, with a minor in pre-optometry and wishes to eventually attend the UCB School of Optometry. She took math, chemistry, optometry and anthropology courses while also working at the Financial Aid Office with the Berkeley Cares Program, informing students on financial aid opportunities. Stephanie enrolled in the UCB summer session and plans on starting an internship during the upcoming fall or spring semester.


Arturo Cisneros

*Arturo Cisneros,* recently transferred to UC Santa Cruz as a junior. Arturo interned with the CfAO at Lawrence Livermore Lab in the summer of 2002. He was recently accepted into the UC “Leads” program and did research this summer at the CfAO with Don Wiberg and Don Gavel. His project was the Optimal Control and Simulations of Lick’s deformable mirror. He plans to pursue a graduate degree in Electrical Engineering, while focusing on microelectronic fabrication and optics.

*Donald T. Gavel,* recently accepted the position of Director of the Laboratory for Adaptive Optics at UC Santa Cruz. Dr. Gavel while an AO researcher at Lawrence Livermore National Laboratory, has been affiliated with the Center for Adaptive Optics since its inception. Don's most recent and current research interests include:
Principal Investigator of a 5-institution collaboration - "Analysis, Modeling and Simulation of Adaptive Optics for Extremely Large Telescopes" and Project Scientist on the "LLNL Astronomical Optics Program" and "Opthalmic Imaging Instruments for the Eye" a DOE Biomedical Grant.

Congratulations to *Austin Roorda* for receiving tenure at the University of Houston. Austin has been a member of the CFAO since its inception and is a member of the Executive Committee.

*David Ginn* the Center's financial analyst for the past two years has moved on to another position off campus. We wish him success in his career and thank him for the great job he has done for us.

# From the Director



Jerry Nelson

The first phase of the Laboratory for Adaptive Optics, funded by the Moore Foundation is planned to be operational by January 2004. Laboratory space was identified, and renovations are currently underway. These are planned to be completed in three phases with partial occupation of the laboratory after phase one. Dr. Don Gavel has accepted the position of laboratory director, Don was formerly with the Lawrence Livermore National Laboratory, where he was an Adaptive Optics scientist and control engineer. Recruitment of additional research and technical staff has proceeded and the team will move from temporary borrowed space into the renovated facility . Research programs for the laboratory include simulation of the conditions that cause the point spread function phenomena and the development of multi-conjugate adaptive optic techniques to minimize the problem.

The annual summer school on Adaptive Optics was held this year August 10$^{th}$ to 15$^{th}$ , with 100 participants including twenty three international attendees. This year the summer school focused on advanced AO and newer areas for its application including confocal microscopy.

The National Science Foundation funds the Science and Technology Centers (STCs) for 10 years, with a mid-term evaluation prior to year 5 that determines whether funding will be continued in years six to ten. The Center underwent this review in April 2003 and was recommended for continued funding through to year ten.

The Center formulated ambitious plans to be implemented over its ten year life. In vision science these are coming to fruition in the form of five AO enhanced instruments for vision correction and retinal imaging. In astronomy the complexity, scale and cost of projected instrumentation are far greater than those for vision science. For most cases they are beyond the resources available to the Center. Consequently the Center has assumed the role of a catalyst for advancing the understanding of AO technology and its deployment in both 10 meter and future 30 meter telescopes. The fundamental studies underway, the development of a high contrast AO system for extra solar planetary detection and the active role Center researchers are playing in studies of a future 30 meter telescope are aligned with this strategy. ■

## Comments on the Annual Adaptive Optics Summer School

The summer school was held from August 10th to 15th 2003. There were a 100 attendees with 23 international visitors. Presentations can be viewed on the CfAO web-page:

http://cfao.ucolick.org/pubs/presentations/aosummer.php#ao03.

*A Sampling of attendees comments follows*:

- The school has been very positive and useful for me. The talks were clear and well arranged.
- Thank you for organizing this great AO summer school!
- Thanks again for a GREAT CfAO Summer School! You and the center staff did a wonderful job and I thought it was well worth the time and travel to attend.
- Thanks for organising the summer school! Everything went very well (as it always does at CfAO events).
- I thought the course was great. Thanks for all your work putting it all together. ■

# Center Activities In the News

## R & D 100 Award – MEMS-based Adaptive Optics Phoropter (Eye Can See Clearly Now)

*Sharon Emery - Lawrence Livermore National Laboratory*

Each day, millions of people use eyeglasses or contact lenses to correct their vision and an increasing number are opting for laser eye surgery. Most of us are familiar with the steps necessary for a vision eye exam. The optometrist or ophthalmologist usually leads us into a darkened room where we're asked to peer into an odd-looking device covered with knobs and dials (called a phoropter). We then proceed to answer a series of repetitive questions: "Which looks better . . . this one . . . or this one . . . number one . . . or number two?" etc. Finally we make a decision and because of its subjective nature remain uncertain as to whether it is the optimal one. In the future, because of an exciting, new optical device developed at Lawrence Livermore National Laboratory, this experience will be less subjective and the resulting prescription greatly improved.

Through a cooperative effort, a MEMS-based Adaptive Optics Phoropter (MAOP) has been developed which will enable clinicians to measure and automatically obtain the optimal vision corrections. In addition, prior to surgery or being fitted with custom contact lenses, patients can view corrected images that have the visual acuity they can expect to see on completion of the procedure and offer feedback. Much of the improved acuity of the vision correction results from the fact that the current standard phoropter addresses only the lower-order aberrations (defocus and astigmatism), while the new system takes into account the higher-order aberrations (coma, spherical aberration, trefoil, quadrifoil, etc.). This better vision correction especially favors those anticipating custom contact lenses or laser refractive surgery. In addition, future versions of MAOP will incorporate retinal imaging, providing clinicians an improvement on the fundus camera currently used to diagnose and treat retinal diseases that cause blindness such as retinitis pigmentosa, glaucoma, diabetic retinopathy and macular degeneration.

*For their work, the MAOP team has been awarded an R&D 100 Award.*

### About MAOP

Development of the MEMS-based Adaptive Optics Phoropter was funded by the Department of Energy (DOE) and the Center for Adaptive Optics (a National Science Foundation Science and Technology Center) in a unique collaboration between universities, national laboratories and industry. It brings together optical component manufacturers and one of the world's leading providers of custom contact lenses and refractive eye surgery equipment. The MAOP system combines current "best-of-breed" technologies to provide optimal vision correction and improve diagnosis and treatment for those suffering from ophthalmic and retinal diseases.

In practice, an eye exam with the MAOP will be similar to that with a standard phoropter. As is current practice, the patient will observe a visual scene (e.g., an eye chart) through a viewport and after the correction has been made be asked to comment if the image appears clearer (a subjective response). The clinicians' experience will also be unaltered, except for the elimination of many of the manual steps required for standard phoropters. However the vision correction obtained with the MAOP system will be significantly improved and more precise than current practice.

### Use of Adaptive Optics

The same adaptive-optics technology used in advanced telescopes for high-resolution imaging of astronomical objects is used in

## MEMS Adaptive Optics Phoropter

MAOP . However, the development of Micro-Electro-Mechanical Systems (MEMS) deformable mirror technology has significantly reduced the mirror size and that of the instrument. The latter also uses off-the-shelf commercial components, enabling the system to be both affordable and small enough for a doctor's office.

A patient having his vision evaluated with a MAOP is instructed to look through the viewport at a target/chart. A light source (superluminescent diode) is then focussed onto the patient's retina and is reflected. A flip-in mirror diverts the optical path and enables the clinical measurements to be obtained via a standard Shack-Hartmann wavefront sensor (WFS) linked to a computer. Then, with a push of a button, the clinician can get the response of the patient to the image resulting from the Adaptive Optics (deformable mirror) correction of the wavefront. For this to happen the computer uses the data from the WFS to adjust the 144 actuators of the MEMS deformable mirror to correct the detected phase change. The wavefront sensor and corrector are the key components for the correction of higher-order aberrations.

The modular MAOP design allows it to be readily modified for other applications. Modules are currently under construction that would enable the system to also perform relatively high resolution retinal imaging. The current retinal imaging device used by clinicians is the Fundus camera. Its imaging systems have limited resolution because wavefront correction cannot be applied. Consequently it is difficult to detect the early-stage of retinal disease or determine the effect of new drug therapies in the treatment of eye disease.

**Advantages**

It is known that higher-order vision aberrations increase with an individual's age and currently these are not corrected by standard phoropters. The aging "baby boomer" generation creates a greater need for diagnosing and treating these aberrations and the MAOP is positioned to meet this need.

Clinical studies conducted at the University of Rochester, with earlier versions of the MAOP system, demonstrated another benefit from correcting higher-order aberrations : Patients with vision far below normal (eg 20:400) experienced significant vision improvements after correcting for higher-order aberrations. In one case there was a 24x improvement in vision. Thus MAOP technology provides a means of enhancing the quality of life for patients having very poor vision that is not amenable to standard correction.

The higher resolution images obtained with MOAP used in camera mode offers a new tool in the battle against retinal disease. For example, MAOP systems (in retinal imaging mode) could provide verifiable assessments for the effectiveness of new therapeutics in clinical trials. This would enable drug manufacturers to gain earlier FDA approval, shortening the time required for the drug to become available to the public.

While other specialized Adaptive Optics retinal cameras are under development, the MOAP imager will provide higher resolution images than those obtainable from the current fundus camera. In addition, from the clinician's perspective, tech staff need only be trained on one instrument, which because of its multiple applications reduces the number of instruments needed.

Finally, a major advantage of MAOP system, is that patient vision information, based on their responses, can be automatically collected and stored at all stages before and after the correction.

**Summary**

The MEMS-based Adaptive Optics Phoropter is the first system that measures

# Center Activities In the News

## MEMS Adaptive Optics Phoropter

higher-order aberrations in the human eye, automatically applies corrections, and provides visual feedback to the patient. This methodology provides both the necessary objective information for the clinician and subjective information needed to assure the patient of a positive outcome when either custom contact lenses or laser eye surgery is under consideration. In addition, relative to today's procedures, it offers the potential for greatly improved visual acuity for patients who have undergone vision correction. The MEMS-based Adaptive Optics Phoropter has the potential to improve the quality of life for those suffering vision loss and blindness caused by retinal diseases and for the millions of people—in particular, our aging baby boomers—who depend on vision correction to just make it through the day.

**Acknowledgements**
This technology has been funded by the Department of Energy and the Center for Adaptive Optics (a National Science Foundation Science and Technology Center).

**The Phoropter Team***
From left,
Kevin O'Brien,
Abdul Awwal,
Steve Haney (Sandia National Laboratory),
Steve Jones,
Brian Bauman,
Steve Eisenbies -Sandia
Seated,
Don Gavel,
Scot Olivier
*Not Present*
Ian Cox: Bausch & Lomb; Paul A. Bierden: Boston Micromachines Corp., David Williams: University of Rochester; and Dan Neal: Wavefront Sciences.

**Non LLNL members are identified*

## Iris AO wins Business Plan Competition

Iris AO, maker of tiny mirrors for adaptive optics, won the $50,000 first prize plus $10,000 in business and legal services in the inaugural Purdue University Life Sciences Business Plan Competition. Iris AO also won two business plan competitions last year, earning more than $75,000 in prizes. Nathan Doble a co-founder of the company said,
"We have been boot-strapping and building the company off our winnings. We now have orders and contracts, and we hope our new mirrors meet the needs of industry."
The mirrors currently used in adaptive optic systems are about 3 inches in diameter and cost about $125,000. The goal of Iris AO is to make mirrors that are less than a half-inch in diameter and cost about $1,000 — but have better performance, Doble said.
*As reported in the Democrat and Chronicle April 26th 2003.*

# Center Activities In the News

## Astronomers Detect Plasma At Black Hole (From Science Daily Sept. 8 2003)



UCLA astronomers report they have detected remarkably stormy conditions in the hot plasma being pulled into the monstrous black hole residing at the center of our Milky Way galaxy, 26,000 light years away. This detection of the hot plasma is the first in an infrared wavelength, where most of the disturbed plasma's energy is emitted, and was made using the 10-meter Keck II Telescope at the W.M. Keck Observatory in Hawaii.

Plasma is a hot, ionized, gas-like matter — a fourth state of matter, distinct from solids, liquids and gases — believed to make up more than 99 percent of the visible universe, including the stars, galaxies and the vast majority of the solar system.

"Previous observations at radio and X-ray wavelengths suggested that the black hole is dining on a calm stream of plasma that experiences glitches only 2 percent of the time," said Andrea Ghez, professor of physics and astronomy at UCLA, who headed the research team. "Our infrared detection shows for the first time that the black hole's meal is more like the Grand Rapids, in which energetic glitches from shocked gas are occurring almost continually."

"I see this as a real breakthrough," said Mark Morris, a UCLA professor of physics and astronomy, who worked with Ghez. "It's a big leap, not just an incremental advance."

"One of the big mysteries in studies of the black hole at the center of our galaxy is why the surrounding gas is emitting so little light compared to black holes at the center of other galaxies," Ghez said. "We now have a completely new and continuously open window to study the material that is falling onto the black hole at the center of the Milky Way."

The past two years, Ghez and her colleagues used adaptive optics at the Keck Observatory to get high-resolution images at wavelengths between the short near-infrared, where stars dominate, and the mid-infrared, where dust dominates.

"There's a history of false detections of this source in the infrared," Ghez said. "At short wavelengths, it's challenging because there are so many stars. In the mid-infrared, it's difficult because there is so much dust at the center of the galaxy. Our observation was successful because it was made between these two problematic regimes with an adaptive optics system. This type of observation only became possible last year."

"We are highly confident in our detection," Ghez added. "We have a bright source at exactly the right spot, right on the black hole, and with properties that are unlike the stars around it; the source emits much more strongly at long wavelengths than the stars, and the source doesn't move, while the stars move at huge velocities. What's exciting and important is not just that we detected the plasma, but that it varies dramatically in intensity from week-to-week, day-to-day, and even within a single hour. It's as if we have been watching the black hole breathing."

Ghez's co-authors include Morris; UCLA physics and astronomy professor Eric Becklin, who identified the center of the Milky Way in 1968; California Institute of Technology research scientist Keith Matthews, and UCLA graduate student Shelley Wright.

The research is federally funded by an individual grant from the National Science Foundation, the National Science Foundation's Center for Adaptive Optics, and the Packard Foundation. It has been submitted for publication to the Astrophysical Journal Letters and is available at http://xxx.lanl.gov/abs/astro-ph/0309076. Ghez provides more information, images and movies, at http://www.astro.ucla.edu/research/galcenter/. ■

# Center Activities In the News

## Interferometry gives eye camera a new lease of life (From Opto & Laser Europe May 2003)

*A retina camera that combines adaptive optics with optical coherence tomography is generating images of retinal cells with unprecedented resolution. Rob van den Berg discovers that it could lead to early detection of glaucoma.*

A US expert in retinal imaging is pushing ophthalmoscope technology to its limits to try to achieve that goal. Donald Miller - who carried out much of his initial research at the University of Rochester, US, but now heads his own group at the University of Indiana - has developed a highly sensitive camera that can generate image slices of the retina to a lateral and depth resolution of just a few micrometres (2 and 4 μm respectively). At the recent Photonics West conference in San Jose, US, Miller presented the first results of his work.

"In contrast to what you might expect, the human eye has significant optical defects - aberrations that distort a passing wavefront, blur the retinal image and degrade our visual experience," explained Miller. "Another, and often larger, source of retinal image blur is diffraction, which is caused by the finite size of the eye's pupil. Both effects not only limit what the eye sees looking out, but also determine the smallest internal structures that can be observed when looking into the eye with a microscope."

**Adaptive Optics**

This is where adaptive optics, a technique developed for astronomy that compensates for wavefront distortion induced by atmospheric turbulence, can help. By analysing the amount of distortion and correcting for it with a deformable mirror, it is possible to obtain sharper images of stars and other stellar objects. In a similar way, it is possible to measure the aberrations of the eye and compensate for them to obtain higher-resolution images of the retina. This is important as photodetector cells in the retina can be as small as 4 μm in diameter.

**Confocal Microscopy**

In 1997 Miller's team constructed the first retina camera based on adaptive optics. "With this camera we were able to see individual photoreceptor cells in the fovea [the part of the retina that gives the sharpest vision]. This was a major breakthrough, but these cells turned out to be the easiest to detect due to their relatively high contrast and brightness," said Miller. "Studying other parts of the retina at the cellular level has proved much more difficult. The retina is organized into well-defined cell layers that are tightly stacked one on top of the other. Reflections from the layers create a host of superimposed images at the detector with the brightest reflections masking the fainter ones."

One way to image the retina's different layers is to use a confocal scanning laser ophthalmoscope. A focused laser beam is scanned across the retina at the desired depth, and the reflected light is detected. This makes "optical sectioning" possible.

By combining this approach with adaptive optics, scientists have already achieved good images of the retina. However, Miller wanted to see if performance could be further improved. "The first and only confocal scanning laser ophthalmoscope (cSLO) using adaptive optics was developed in 2002 at the University of Houston, and achieved a 2-3 times increase in axial [depth] resolution over commercial cSLOs," he said. "Its 110-150 μm axial resolution was a big improvement, but is still much larger than cells in the retina and so provides only coarse sectioning of the retina, whose total thickness is a few hundred micrometres."

# Center Activities In the News

## Interferometry Eye Camera



**Optical Coherence Tomography**
Miller decided to try to solve the sectioning problem using an entirely different approach: optical coherence tomography (OCT). In OCT the "time of flight" and intensity of reflected optical waves is measured using interferometry. Typically, a Michelson interferometer is used to split the light beam into a reference beam and a signal beam. While the former is reflected from a mirror, the latter is backscattered from the sample under investigation. An interference signal (image) is then generated for reflections with a path length that matches that of the reference beam. By precisely controlling the length of the reference arm, it is possible to perform imaging at different depths within the sample.

A sophisticated retina camera that combines the enhanced lateral resolution of adaptive optics with the high axial resolution of OCT has now been built in Indiana. The camera can image the living human retina with a tiny voxel (3D pixel) volume of 44 $\mu m^3$ - more than 340 times smaller than that of the commercial cSLO.
"We managed to record high-resolution images at different depths in the human retina. Although we are not certain yet how to interpret these, the variation in pattern that we see at the cellular level suggests that we are looking at real retinal structure," said Miller. "We have achieved a depth resolution of 14 µm - an order of magnitude better than the adaptive optics cSLO - using a superluminescent diode (SLD) with a very short coherence length."
The Indiana camera consists of three independent optical circuits. There's an adaptive optics system for compensating any optical distortion; a one-dimensional (1D) OCT imaging system for depth profiling and reference purposes; and a two-dimensional (2D) OCT for capturing 2D image slices of the retina at any depth.

**The System**
The light source for each system is an SLD operating at a distinct wavelength. SLDs are favoured over other laser sources because their short coherence length diminishes the problems associated with laser speckle, an optical interference effect that degrades image quality in OCT systems.
"To reduce the effects of speckle we are looking at light sources with better spatial properties," said Miller. "We are also evaluating faster read-out detectors and real-time image-processing electronics to reduce the acquisition and processing time, making the instrument more clinically viable."

The adaptive optics system consists of a Hartman-Schack wavefront sensor, which measures wavefront error, and a deformable mirror that uses 37 actuators to adjust its shape and make wavefront corrections. This wavefront correction system uses a low-power 788 nm SLD and closed-loop control to perform up to 22 wavefront measurements and corrections per second. The exposure level at the eye is less than 7 µW - 80 times less than the maximum exposure recommended by the American National Standards Institute.

The 2D OCT imaging system comprises a scientific-grade CCD camera, an interferometer and a 10 mW SLD operating at 679 nm. The length of the interferometer's reference arm is adjusted by a voice-coil connected to a piezoelectric mirror.

The 1D OCT system is needed because even minimal motion can degrade or mis-register the image. Involuntary head and eye movements and pulsations of the eye can induce random changes in the distance between the retina and the CCD camera in

# Center Activities In the News

## Interferometry  Eye Camera

the 2D OCT system.

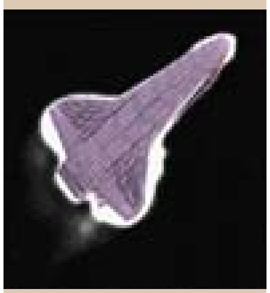
In order to compensate for these movements, Miller gas come up with a tracking scheme that uses an 856 nm SLD to perform an ID OCT scan 20 times per second, traversing the retina's full depth at just one location. This serves as as a reference to keep the retina in exactly the right position.

**Applications**

Potential applications include the detection of local pathological changes and the investigation of the function of retinal layers. Its sensitivity could mean more accurate observations at the head of the optic nerve, or population counts of ganglion cells.

The camera may even be able to detect the onset of glaucoma, a leading cause of blindness in the West that is caused by the gradual loss of optic nerve fibres. Currently, glaucoma can only be detected after significant damage has occurred. The detection of diabetes could also be improved - the disease leads to microaneurysms in the retinal blood vessels, also causing blindness. “The retina camera might also contribute to a deeper scientific understanding of the light-collecting properties of the retina,” said Miller, “in particular, the spatial arrangement and relative numbers of cone and rod photoreceptors, which transform photons into neural signals.”

## Adaptive Optics Researcher Aids Space Shuttle Investigation



The enhanced image of the plasma field surrounding the Columbia. The wire model of the spacecraft has ben inserted to aid perspective

Dr. Julian Christou, a research specialist at the Center for Adaptive Optics, used his image processing skills to help NASA in its investigation of the space shuttle Columbia disaster - Columbia broke up during reentry on February 1, killing all seven astronauts aboard.

Christou, who has done pioneering work on a method of image processing called “blind deconvolution,” contacted former colleagues at Kirtland Air Force Base in New Mexico in February to see if he could help enhance images of the shuttle.

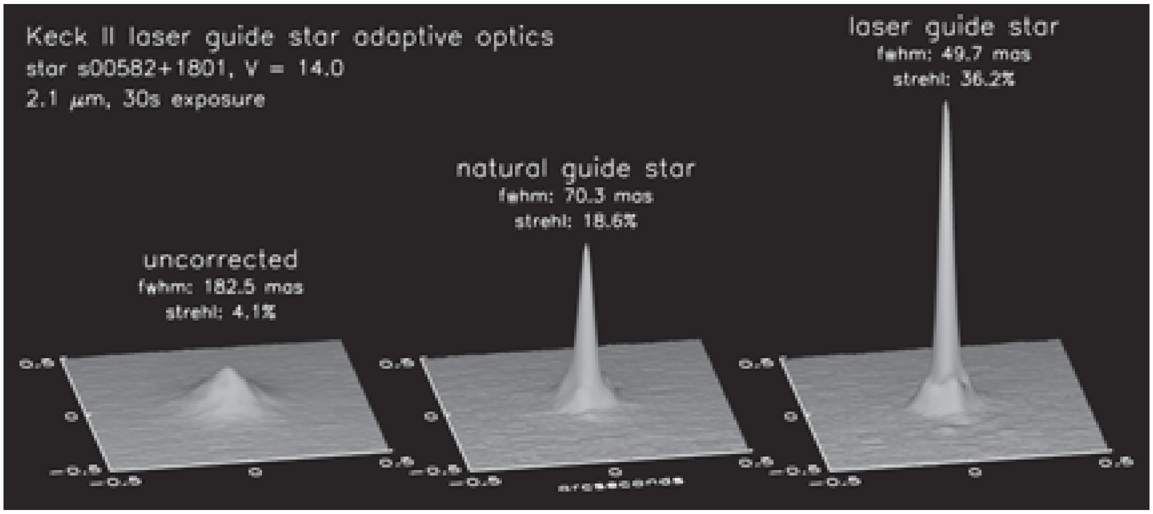
The Air Force referred Christou to NASA, which sent him two photos taken at Kirtland three minutes before the shuttle broke up. Using his blind deconvolution technique, Christou was able to make the images much clearer for investigators.. These enhanced images were sent to NASA for further analysis.

“It was very helpful,” said Lt. Col. Woody Woodyard, spokesman for the Columbia Accident Investigation Board. The CAIB report is available from http//www.caib.us/

The investigation board has been examining the photos for anything out of the ordinary, Woodyard said.

*The enhanced images were discussed in the investigation board’s March 18 press briefing. They were also featured in an article about the investigation that appeared in Aviation Week and Space Technology.*

## First Light for Keck Laser Guide Star Adaptive Optics Correction




Point Spread Function for a V = 14.0 star
a. Uncorrected,
b. Closing the AO loop with the star as the guide star,
c. Using the laser guide star as the reference star.

The Keck Adaptive Optics (AO) team announced that it had achieved the first corrected images using the Keck laser guide star (LGS) AO system on the night of September 18th 2003.

The success criteria for this first light milestone were fully achieved; primarily a Strehl of > 20% at K' using a NGS > 13 mag as the tip/tilt star.

On the second night excellent seeing conditions allowed the system to achieve a Strehl of 36%, with a 50 milli-arcsec FWHM, using a 14th magtip/tilt star in a 30 sec NIRC2 K'-band image. The LGS itself was ~ 9.5 magnitude with a FWHM ranging between 1.4 and 1.8 arcsec. Significant technical progress in support of this milestone included: implementation of a new tip/tilt sensor (STRAP), implementation of a low bandwidth wavefront sensor used to correct the focus of the wavefront sensor and to provide centroids for image sharpening, tracking of the LGS wavefront sensor focus versus elevation, laser pointing, and some preliminary automation of the observing scheme ■

AO team members who achieved this milestone included from left Doug Summers, Scott Hartman, Peter Wizinowich. Adam Contos, Paul Stomski, David Le Mignant, Antonin Bouchez, Marcos van Dam and Erik Johansen.

On the Mountain were Robert Lafon, Jason Chin, Julie Rivera, and David Lynn .

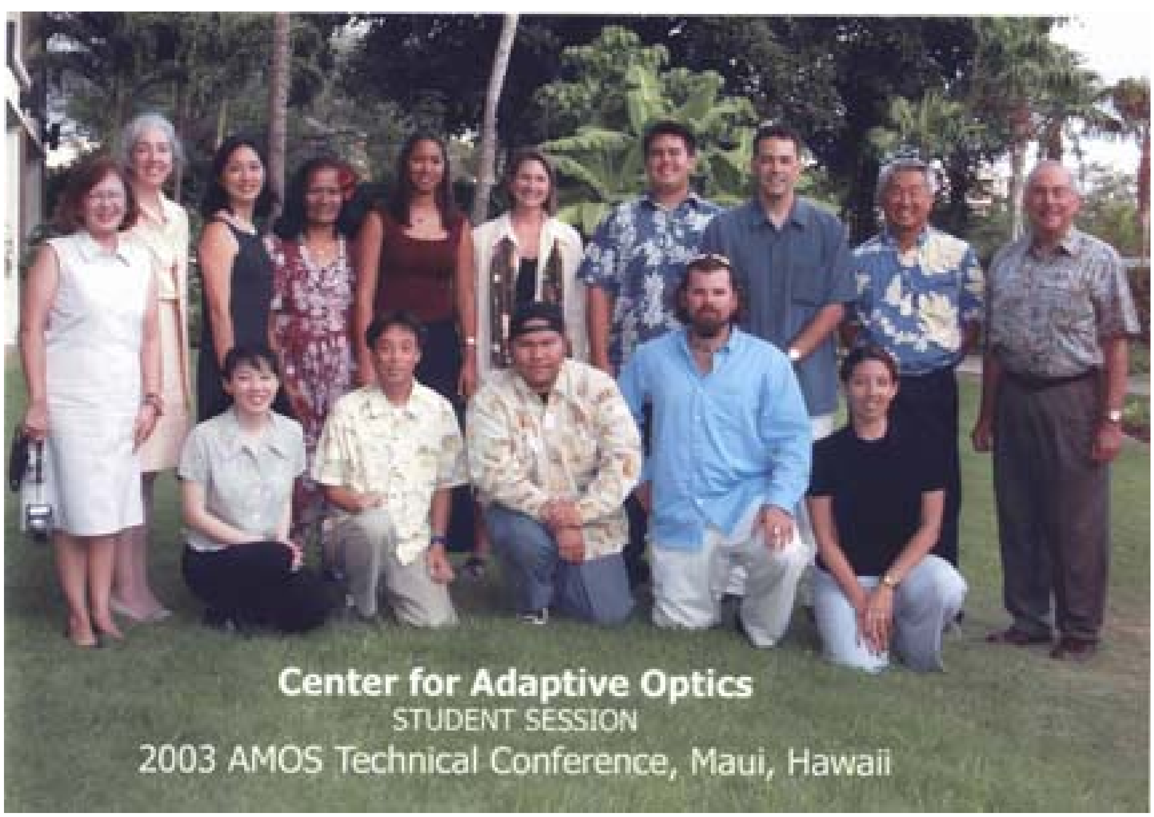
# Education and Human Resources



This summer, CfAO's Education and Human resources theme accepted 24 undergraduate students into their Science, Engineering and Technology Training (SETT) programs the first on the mainland and the second – the Akamai internship program in Hawaii. The latter was implemented as a continuation of our efforts to develop industrial partnerships in Hawaii. Applicants who were Maui residents were offered research positions at Maui high tech companies. In the mainland program, undergraduates from community colleges and 4-year institutions were offered positions at CfAO institutions across the nation.

In both programs the students research experience began with a week-long orientation or short course to introduce them to the fundamentals of astronomy, vision science, optics, and general research practices. These courses were taught by CfAO members who implemented the inquiry-based teaching techniques recently learned at the Maui Professional Development Workshop held in May.

At the completion of their research experience, the interns prepared scientific presentations and posters. The mainland students successfully presented these at a student symposium held in August, as part of the annual Adaptive Optics Summer School, in Santa Cruz. The Akamai interns did so at a special student session at the September AMOS technical conference in Maui. Twelve undergraduate students affiliated with CfAO education presented posters at the SACNAS (Society for the Advancement of Chicanos and Native Americans in Science) student conference this October in New Mexico. Presenting scientific research at a national conference or a student symposium for the first time, is nerve wracking and a huge accomplishment for these undergraduates. We congratulate them and wish them luck in their future academic endeavors.




Back row: Wallette Pellegrino (Maui Community College, Asst. Prof. Coopertive Education), Leslie Wilkins (Maui Economic Development Board Vice President and Director), Jeanne Skog (Maui Economic Development Board President and CEO), Ms. Kuluhiwa (proud parent), Kawailehua S. Kuluhiwa (Akamai intern), Lisa Hunter (Center for Adaptive Optics director of education and human resources), Charles Oliveira (Akamai intern), Mike Ecsedy (Akamai intern), Clyde Sakamoto (Maui Community College), Joe Janni (AMOS) front row: Jennifer Tom (Akamai intern), Ivan Won (Akamai intern), James "B.J." Hoopii (Akamai intern), Richard Cariens, Jr. (Akamai intern), Malika Moutawakkil (Center for Adaptive Optics, education coordinator)

## 2003 Internship Host Sites and Advisors

| Akami | Mainland |
|---|---|
| Boeing<br>*Advisors* - Ken Maskery, Lewis Roberts | Indiana University<br>*Advisor* - Donald Miller |
| Trex<br>*Advisors* - Rusty Hughes, Jason Zhang | Jet Propulsion Laboratory<br>*Advisor* - Mitchell Troy |
| Akimeka:<br>*Advisor* - John Forsythe | Lawrence Livermore National Lab<br>*Advisors* - Scot Olivier, Kevin Baker, Kai N. Lafortune |
| IFA<br>*Advisors* - Les Heida, Andrew Hraha, Haosheng Lin | University of Houston<br>*Advisors* - Thomas J. Hebert, Austin Roorda, Jason Marsack Krishnakumar Venkataswaran |
| MHPCC<br>*Advisors* - Mark Skinner, Tak Sugimura, Mike Berning | UC Los Angeles<br>*Advisors* -Andrea Ghez, James Larkin, Seth Horntstein, Matthew Barczys |
| Oceanit:<br>*Advisors* - Ken Maskery, Dan O'Connell | UC Santa Cruz<br>*Advisors* -Jerry Cabak, Sandra Faber, Christopher Wilmer, Chris Wright |
| W.H. Keck Observatories<br>*Advisors* - David Le Mignant, Kyle Kinoshita, Randy Campbell | University of Rochester<br>*Advisors* -David Williams, Jason Porter, Stacey Choi, Nathan Doble |

### Stars, Sight and Science

The Center completed their third successful summer with the Stars, Sight and Science (SSS) program. Each year, fifteen students from high schools across California are se-

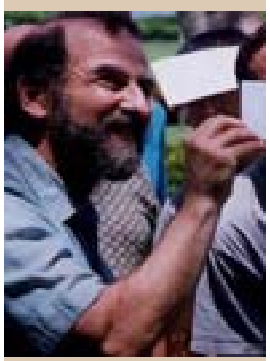
Back row from left Gary Martindale, Jason Porter Nick Konidaris, Lynne Raschke, Scott Severson, David Lai, Lew Yonemoto, Scott Seagroves, Next row: Maribel Huerta, Becky Aguirre, Cynthia Cervantes, Jessica Garcia, Jackie Anchondo, Vanessa Cortez, Nate Abrego, Rosalina Bonilla, Maria Bernice De Real, Jennifer Hsieh, Next row: Hugo "Keike" Herrera, Mindy Duong, Myra Novarro, Marla Geha, Mary Lou Juanatos, Front row: Leo Do

# Education and Human Resources (Continued)

lected to participate in a 4-week residential science experience offered in collaboration with the UC Santa Cruz COSMOS program. The curriculum includes three courses taught in parallel: Astronomy, Vision Science and Science Communication. Stars, Sight and Science provides a dynamic teaching "laboratory" for CfAO members to practice inquiry-based teaching techniques they acquired at the Professional Development workshop in Maui. In addition to course and laboratory work, students went on field trips to UC Berkeley, The Exploratorium and the Lick Observatory

We would like to thank the following people for all their hard work with the Stars, Sight and Science Students this summer 2003:
David Lai, UCSC, Astronomy Project Advisor
Elinor Gates, Lick Observatory, Astronomy Project Researcher
Gabriel Klapman, UCSC, Vision Science Teaching Assistant
Gary Martindale, Watsonville High School, Teacher Fellow
Gene Switkes, UCSC, Vision Science Consultant and Instructor
Jason Melbourne, UCSC, Astronomy Project Advisor
Jason Porter, University of Rochester, Lead Vision Science Instructor
Jim Lewis, UCSC, Eyeball Dissection Instructor
Joy Martin, University of Houston, Vision Science Instructor
Lynne Raschke, UCSC, Lead Astronomy Instructor
Maribell Huerta, UCSC, Vision Science Project Advisor
Marla Geha, Observatories of the Carnegie Institution, Astronomy Project Advisor
Nick Konidaris, UCSC, Astronomy Project Advisor
Pascha Bueno, UCSC, Science Communication Instructor
Scott Seagroves, UCSC, Astronomy Project Advisor
Scott Severson, UCSC, Lead Astronomy Instructor.

## CfAO Collaboration with the Exploratorium



Barry Kluger-Bell

Over the last few years, the CfAO has been working with the San Francisco Exploratorium creating the Professional Development Workshop. Annually this involves approximately 30 CfAO graduate students, postdocs, and educators in acquiring the techniques of inquiry-based science teaching.

The workshop has become a central project for EHR, significantly impacting education and the Center community, and expanding partnerships in Hawaii. Barry Kluger-Bell a leading member of the project team was recently funded as a CfAO project leader to formalize the CfAO/Exploratorium partnership. His role is to lead the development of the inquiry training elements of the workshop, refine existing workshop elements as well as develop new elements to serve the wide-ranging needs of the CfAO community. Another key member of the workshop team is Candice Brown. She is a science educator at the Exploratorium, who has developed many elements of the workshop and is actively involved in generating new activities for workshop participants returning for a second, third or fourth year.

The CfAO welcomes the Exploratorium as a new partner.

# A Pictorial Record:
# CfAO 2003 Spring Retreat, San Jose, CA



Andrea Ghez, Gaspard Duchene and David Le Mignant continue their discussion after dinner

Jose Milovich and Matthew Britton see the "light"

James Lloyd, Brett Ellerbroek, Anand Sivaramakrishnan, and Miska Le Louan debate the finer points of exhibit viewing

Lisa Poyneer and Don Wiberg share a moment before lunch

Michael Helmbrecht and Joy Martin watch Denise Kaiser (seated) have a robot do a portrait

# Center for Adaptive Optics

### Laser Guide Star, First Light at Keck Observatory

A very faint beam from the Keck sodium laser appears in this 20-minute exposure. The laser creates a "virtual" star high above the Earth's surface, which is not visible to the human eye, but is bright enough to guide high resolution adaptive optics at Keck. This photo was taken from 600 meters away. Hazard lights from an automobile mark the steep descent path of the summit, and the motion of the Earth has created star trails in the sky. Photo by John McDonald from Canada France Hawaii Telescope Corp. (CFHT) - First Light Dec. 23rd. 2001. ■

**Extract from CfAO's Mission Statement**

"Our purpose is to advance and disseminate the technology of adaptive optics to serve science, health care, industry, and education."

*The National Science Foundation Science and Technology Center for Adaptive Optics, University of CA 95064 Santa Cruz, California*
*Phone: (831) 459 5592*
*Fax: (831) 459 5717*
*email: cfao@ucolick.org*