Center for Adaptive Optics

Winter 2002, Volume 2 , Issue 1

Adaptive Optics Scanning Laser Ophthalmoscope for Retinal Imaging

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Fig 1: The AOSLO group at the University of Houston College of Optometry: Members of the lab, from left to right are Khalid Chaudry, Tom Hebert, Joy Martin, Fernando Romero-Borja, Siddharth Poonja, Krishnakumar Venkateswaran, Hope Queener, Jason Marsack, Austin Roorda and Ramesh Sundaram.

Adaptive optics (AO) is a powerful tool that has been used over a decade to overcome degradation of image quality caused by atmospheric turbulence while imaging astronomical sources using ground-based telescopes. In recent years, scientists working in retinal imaging have applied this technology for imaging microscopic features in the eye. In retinal imaging, the limits to microscopic imaging of the human eye are the monochromatic aberrations of the cornea, the lens, ocular medium – aqueous, vitreous, the weakly scattering cells and tissues in front of the retina. These aberrations vary between individuals. Therefore, imaging the live human retina at very high spatial resolution also requires adaptive optical correction.

High resolution imaging of the live human retina gives clues and has the potential to help in the early detection and treatment of diseases, thereby helping in the prevention of vision loss. Some of the typical conditions like, hemorrhages of capillaries in diabetic patients' eyes, formation of exudates, or detection of macular holes can be studied at microscopic scales. Studying basic properties of photoreceptors at high spatial and temporal resolution has the potential to revolutionize our understanding of human vision with potential application in fields such as robotic vision. The two major components of an adaptive optics system are a wavefront sensor and a

Continued - Retinal Imaging P2

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Retinal Imaging

deformable mirror. Liang et. al. (1994) were the first to demonstrate the use of a Shack Hartmann wavefront sensor to measure the monochromatic aberrations in the eye. Later, the AO group at the University of Rochester incorporated the wavefront sensor into adaptive optics ophthalmoscope (Liang et al., 1997). The use of AO improved the quality of retinal images obtained using a CCD fundus camera to an extent that made it possible to measure the properties of microscopic features in the retina, such as photoreceptors. Our group has more recently combined the conventional scanning laser ophthalmoscope and adaptive optics (Adaptive Optics Scanning Laser Ophthalmoscope – **AOSLO**) to correct for both lower and higher order aberrations to obtain images of unprecedented optical quality (Roorda et al., 2002).

While AO technology for telescopes and vision science are surprisingly similar, the implementations of the technology have some important differences. The differences arise mainly because of the characteristics of the optical system that is being corrected. For example, the isoplanatic angle in astronomical imaging is typically 10 – 20 arc seconds whereas in the case of eye, it is about 1 degree. The magnitude of the tilt term is another major distinction between astronomy and vision science. Saccades and tremor in the human eye are analogous to the beam jitter and drift in imaging through a turbulent atmosphere. The frequency of tremors in the eye peak at about one hundred hertz and saccadic velocities in a fixating eye can reach 70 deg/sec with magnitudes approaching 0.5 deg. The Rochester system records the images using 4 ms flashes and hence is able to freeze the drift and jitter to a considerable extent. In our present AOSLO, we eliminate blur resulting from eye movements by scanning the beam and recording the images at 30 frames per second. However, the high absorption of incident photons by the human retina, combined with safety considerations impose constraints on the amount of light that can be used to illuminate the eye. This results in single image frames being photon-starved and hence noisy. The signal to noise ratio of these images is only improved by off-line image registration techniques. Aberrations higher than tilt remain relatively stable since they originate from the static components in the eye. Nonetheless, dynamic changes in these aberrations, particularly in defocus, are known to occur. Aside from tilt, correction of the aberrations of the eye requires a closed-loop bandwidth of about 3Hz (Hofer et al., 2001).

The Houston AOSLO

At Houston, AO is being used in a scanning laser ophthalmoscope, or SLO. In a SLO, the image is acquired temporally, by measuring the scattering of light from a focused spot. The raster scans the point across the region of interest on the retina. In our SLO, a resonant-scanner and galvanometric scanner combination is used to scan the retina at ~ 16 KHz horizontal

scan and ~ 30 Hz vertical scan (Electro-Optics Products Corp, Flushing Meadows, NY). The light from the retina is descanned and focused onto a pinhole. The 3.5 mm exit beam is collected using a 100 mm focal length collector lens and imaged onto a pinhole. A pinhole of 80 μm diameter is used in our system. The light through the pinhole is detected using a GaAs photo multiplier tube (Hamamatsu, Japan). The role of the confocal pinhole is to reject light from planes outside the plane of focus, which gives the SLO the ability to perform axial sectioning.

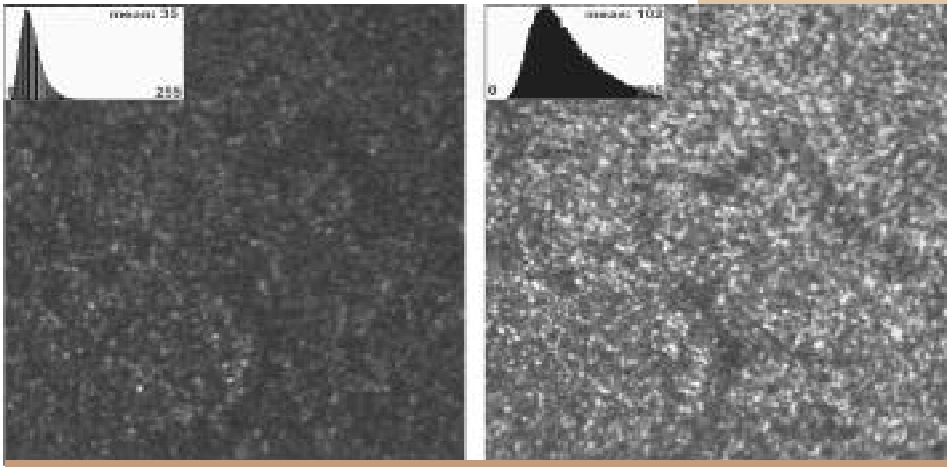

Fig 2: The left panel shows an image obtained with Adaptive Optics turned off and on the right is the image obtained using AOSLO with Adaptive Optics turned on. Scale bar is about 100 microns

AO in SLO, improves both the focused beam of light that is imaged onto the retina as well as the focused image on the confocal pinhole. In our system, the Shack-Hartmann wavefront sensor takes 241 samples on the wavefront. Zernike modes are computed based on the wavefront slope measurements at these 241 points. Up to 8th or even 10th order Zernike modes are fitted to the wavefront slope measurements.

Voltages are then generated and sent to a 37 channel deformable mirror (Xinetics, Andover, MA), which corrects the wavefront. AO correction and retinal imaging are done simultaneously in the AOSLO. We use the same light that scatters from the retina for wavefront sensing, but try to split off as little as possible, since we want to maximize the number of photons for imaging. With the small fraction of light available for wavefront sensing, our integration time for each wavefront measurement takes about 100 – 200 msec and our closed loop bandwidth ranges from 0.1 to 0.2 Hz.

Houston AOSLO results

In the presence of aberrations, the typical lateral resolution is >6 μm. With AO, the lateral resolution is improved to better than 3 μm. Fig 2 shows the improvement in image quality with and without adaptive optics. AO corrected images are obtained with higher light throughput and higher spatial resolution.

A major advantage of a confocal system is its ability to optically section the retina, which is thin, weakly scattering multi layered tissue. Fig 3 shows the axial sectioning of a human retina imaged using the AOSLO. In the presence of aberrations, the typical axial resolution is ~ 300 μm. With adaptive optics, the axial resolu-

Continued - Retinal Imaging P4

Retinal Imaging

tion of the AOSLO can be as low as 30 µm in a perfect eye. However, the residual aberrations in a real human eye after AO corrections, combined with the necessity to use a larger pinhole to increase light collection, leave us with an axial resolution that is currently around 120 µm. Reducing the diameter of the confocal pinhole will result in better axial sectioning but this can be done only at the cost of loss in intensity. For our AOSLO, we use an 80 µm pinhole. The figures show the images obtained using the current AOSLO demonstrating its lateral and transverse resolution capabilities.

The real-time imaging in the AOSLO has made it possible, for the first time to resolve single white blood cells flowing through the smallest capillaries, without using fluorescent dyes injected into the blood stream. Real time video of living human retinas with blood flow can be seen at the following website: http://www.opt.uh.edu/research/aroorda/aoslo.htm.

We are involved in several scientific and clinical studies with our instrument but there are many potential applications, ranging from early diagnosis of eye disease to retinal microsurgery, and are too many for one lab to focus on. This is the only instrument of its kind in the world, but similar instruments are under construction. Recently, a NIH bioengineering research partnership grant was awarded to a group of institutions, several of which are members of CFAO (Rochester, LLNL, Houston), to build a new generation of AOSLOs, with enhanced detection and performance characteristics. Commercialization of the technology is also being explored.

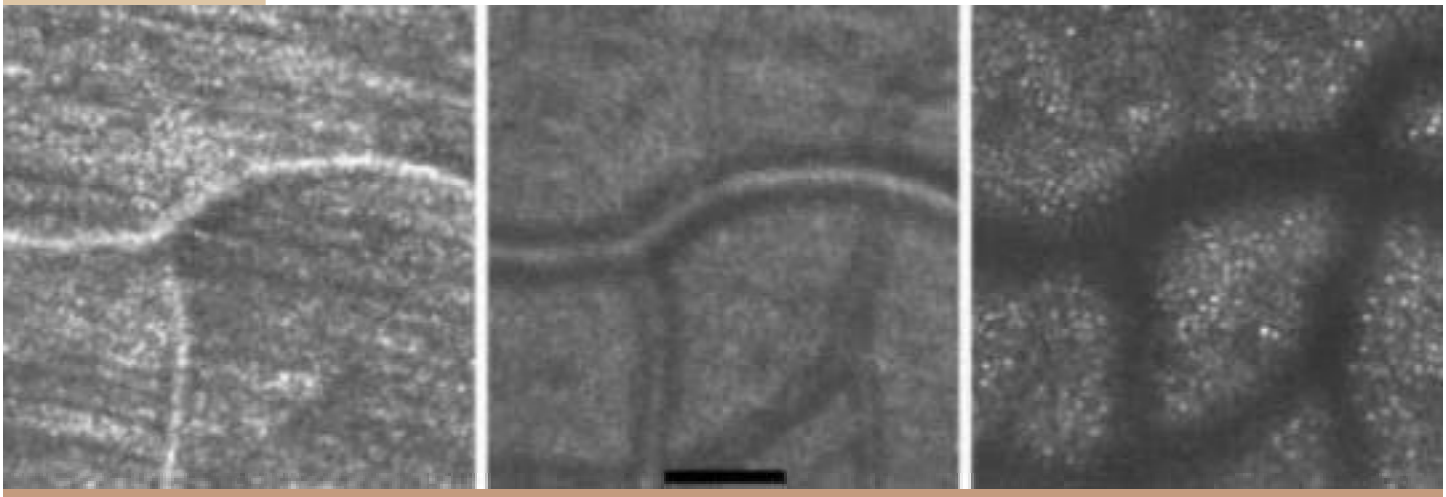

Fig 3. Axial sectioning in a live human retina obtained using AOSLO. The left panel shows the nerve fiber layers, the middle panel the blood vessels and the right panel shows the photoreceptor layer. Scale Bar 100 microns.

Continued - Retinal Imaging P 5

From the Director

Jerry Nelson

The Center for Adaptive Optics (CfAO) has concluded a particularly active and rewarding six months. Over this period the Moore Foundation awarded the University of California Santa Cruz, $9.1 million to establish a Laboratory for Adaptive Optics. Claire Max was appointed the Principal investigator for this laboratory, with Joseph Miller and myself as co- Principal Investigators.

Three Center affiliated groups - the University of Rochester, University of Houston and Lawrence Livermore - were part of a consortium led by the University of Rochester that was awarded $10 million over a period of five years by the National Eye Institute. The consortium will develop six vision related instruments that utilize Adaptive Optics.

Finally, the Center was visited by a National Science Foundation Review team on October 2nd to 4th 2002. The team evaluated the Center's progress over the past year and reported that they were very pleased with progress overall and particularly the Education and Human Resources (EHR) program of the Center.

The EHR held its annual Professional Development workshop in Maui this year. In addition to the instruction on Inquiry based teaching/learning provided to graduate students and postdoc attendees, the workshop was attended by interested members of the Maui Community, including representatives from the US Airforce Observatory at the Maui Space Surveillance System on the summit of Haleakala, science teachers form Maui High Schools and staff from Maui Community College. These interactions are on-going, with the Center collaborating with Maui Community College in the development of a Technology curriculum.

The Center is entering its fourth year and in February 2003 our renewal proposal will be submitted followed by an April 2003 NSF review to determine if it qualifies for another five years funding as a Science and Technology Center (STC). STCs are funded for ten years, subject to satisfactory progress in the first five. We are proud of our achievements to date and are excited by the prospect of another five years of NSF funding. ■

Retinal Imaging

References

Hofer, H., Artal, P., Aragon, J.L., & Williams, D.R. (2001). Dynamics of the eye's wave aberration. Journal of the Optical Society of America A, 18(3), 497-506.

Liang, J., Grimm, B., Goelz, S., & Bille, J.F. (1994). Objective measurement of wave aberrations of the human eye with use of a Hartmann-Shack wave-front sensor. Journal of the Optical Society of America A, 11, 1949-1957.

Liang, J., Williams, D.R., & Miller, D. (1997). Supernormal vision and high-resolution retinal imaging through adaptive optics. Journal of the Optical Society of America A, 14(11), 2884-2892.

Roorda, A., Romero-Borja, F., Donnelly, W.J., Queener, H., Hebert, T.J., & Campbell, M.C.W. (2002). Adaptive optics scanning laser ophthalmoscopy. Optics Express, 10(9), 405-412. ■

Iris AO – Spin off from the Center for Adaptive Optics

Two researchers from the Center for Adaptive Optics, Dr. Michael Helmbrecht from Berkeley Sensor & Actuator Center (BSAC) and Dr. Nathan Doble from the University of Rochester NY, together with Matthew Campbell, a recent graduate from Berkeley's MBA program and Cliff Kollenberg a MS graduate in Materials Science at BSAC, have co-founded Iris AO – a company that has developed low-cost deformable micro mirrors for adaptive optics. The company has already attracted attention, having garnered the $50,000 grand prize at the fourth annual UC Berkeley Business Plan Competition held on April 24 2002 and also the $25,000 grand prize at MBA Jungle's second annual business plan competition in New York, on April 26 2002.

The micro-mirror technology promises to considerably reduce the cost of both diagnostic and vision corrective instrumentation using Adaptive Optics. Such systems under development in laboratories are providing exciting results, but their future widespread use requires low cost robust deformable mirrors that meet certain design specifications. While major markets exist in vision science, these micro mirrors will also improve AO systems for astronomy, particularly systems designed for Extreme AO.■

The Founders of Iris AO

The Founders Unmasked. From left - Michael Helm-brecht, Matthew Campbell, Cliff Knollenberg and Nathan Doble, receiving the grand prize at the MBA Jungle Competi tion.

People and Profiles

Adaptive Optics

Claire Max, Associate Director of the Center for Adaptive Optics, is the Principal Investigator of the Laboratory for Adaptive Optics funded on the UC Santa Cruz campus by the Moore Foundation grant. Max was inducted into the Academy of Arts and Sciences in October 2002.

Sandy Faber was recognized in the November 2002 issue of Discovery Magazine as among the "top 50 women scientists in the country." In addition to being a senior member of the Center for Adaptive Optics at UCSC, Faber has been involved with both the Hubble Space Telescope and the W. M. Keck Observatory in Hawaii. Most recently she lead the team that designed and built the DEIMOS spectrograph, a powerful new instrument installed this year on the Keck II Telescope. Faber's many honors include election to the National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society. In 1995, she was appointed University Professor, the highest honor for faculty in the UC system.

Austin Roorda from the University of Houston received the American Academy of Optometry's prestigious Irving and Beatrice Borish Outstanding Young Researcher Award. The award will be presented at the American Academy of Optometry Annual meeting in December 2002.

.Continued - People and Profiles P7

Education and Human Resource Activities

The summer of 2002 was a particularly active and rewarding time for the Education programs within CfAO. We started with the professional development workshop for graduate students and post docs in Maui.

Maui Professional Development Workshop

In May 2002, CfAO held the second annual conference for Center graduate students and postdoctoral researchers. The workshop was held in Maui, Hawaii. Twenty six Center graduate students and postdoctoral researchers attended, representing both astronomy and vision science. The students toured the Haleakala facilities, AEOS and Mees Solar Observatory and attended a Center-sponsored workshop on inquiry-based learning. Four high school teachers attended and participated in the activities.

The instructors were Barry Kluger-Bell and Candace Brown from the Explorotarium San Francisco, Doris Ash from the Education Department UCSC and two returning graduate students who helped with the instruction, Ann Metevier and Tiffany Glassman. Educators from Maui Community College and High School Science teachers also attended.

Dr. Barry Kluger-Bell leads a class on the principles of Inquiry based teaching

In addition to CfAO, the workshop was supported with funding by organizations within the Maui community, these included:

- Air Force Research Laboratory
- Akimeka
- East-West Center/Pacific Disaster Center
- Maui Economic Development Board's Women In Technology Project
- Maui High Performance Computing Center
- Oceanit
- Science Applications International Corporation
- Textron Systems
- The Boeing Company
- Trex Enterprises

Attendees at the workshop subsequently applied the principles of Inquiry based learning to their teaching sessions for the Internship program and Stars, Sight and Science. Longer term working relationships were also forged with Maui Community College.

People and Profiles (Cont.)

Joy Martin, a CfAO graduate student at the University of Houston pursuing a combined OD (Optometry) and PhD degree,was the National Winner of the 2002 Innovative Research Award, administered by the American Optometric Foundation. The award was the result of a competition among all the colleges of Optometry in the US and Canada that required the submission of a paper based on novel and innovative research related to contact lenses. Joy's paper was entitled "New Applications in Wavefront Sensing: Predicting Visual Performance with Multizone Bifocal Contact Lenses". She was awarded a cash prize of $7000. ■

8

Education and Human Resource Activities

Graduate Students, Seth Hornstein (UCLA) and Lynn Raschke (UCSC) assist intern Jarret Hornstein (University of Hawaii, Hilo) at the orientation workshop

Stars, Sight and Science students and instructors relax during a break in their activities

Internship Program

Community college students and undergraduates from four-year universities can get involved in CfAO research by participating in our internship program. In 2001, students completed internships at University of California, Santa Cruz and Lawrence Livermore National Labs. In 2002 and 2003 the program has been expanded and the CfAO can offer internships through the NSF Research Experiences for Undergraduates (REU) program. Fourteen students participated in the 2002 summer program coming from the following Colleges:

Hartnell Community College, Cabrillo Community College, Napa Valley Community College, Maui Community College, San Jose City College, University of the Pacific, UC Davis, UC Santa Cruz, and University of Hawaii, Hilo.

Prior to commencing their internships, all interns attended an orientation workshop. CfAO graduate students and post docs who had attended the Inquiry based learning sessions in Maui used the orientation workshop to apply the principles of Inquiry Based Teaching. Following the workshop, interns commenced their research experience at one of the following sites:

The University of Rochester, Lawrence Livermore National Laboratory, UC Lick Observatory, UC Los Angeles, and UC Santa Cruz.

On completion of the internships, the students made presentations on their research to attendees at the annual Adaptive Optics Summer school held at UC Santa Cruz.

Stars, Sight and Science

Stars, Sight and Science is a course cluster offered in conjunction with the California State Summer School for Mathematics and Science (COSMOS) program at UCSC. The

Education and Human Resource Activities

Stars, Sight and Science (Continued)

project is also a partnership with the UCSC-based Educational Partnership Center (EPC), and builds on EPC'S relationship with area high schools. The Stars, Sight, and Science (SSS) cluster focuses on middle to high-achieving underrepresented students, providing hands-on, inquiry-based experiences. 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.

Professor Gene Switkes (UCSC/UCB) was the lead instructor for the vision science course, and UCSC graduate student Lynne Raschke for the astronomy course. Many of the instructors in SSS, were graduate students and postdocs who had attended the Inquiry Based Learning Workshop in Maui. Once again they had the rewarding experience of putting into practice the principles of Inquiry learned at the workshop.

The efficacy of this teaching method was evident both in the understanding of the subject matter and the confidencewith which the High School students spoke when making their presentations.

Visions and Voices: Educational Leadership in the Research Center Environment

The National Science Foundation Research Center Educators Network (NRCEN), held a workshop in Santa Cruz, California on October 26 – 28th 2002. NRCEN includes the educational activities of Science and Technology Centers (STC's), Engineering Research Centers (ERC's), and Materials Research Science and Engineering Centers (MRSEC's). The workshop was sponsored by the National Science Foundation through a supplement to the Center for Adaptive Optics (CfAO) Cooperative Agreement No. AST-987683 with additional supplemental funding provided by the Center for Adaptive Optics. Highlights of the workshop included a keynote address *"What does it mean to integrate research and education and why is it so important?"* by Judith Ramaley Assistant Director EHR/OAF, National Science Foundation, and a panel discussion featuring CfAO graduate students on their experience with learning and implementing Inquiry based learning methods.

Featured speakers included: Dragana Brzakovic, Office of Integrative Activities, NSF; Lisa Hunter, Center for Adaptive Optics; David Burgess ,Boston College; Shirley Malcom,American Association for the Advancement of Science; and Peter Bruns, Howard Hughes Medical Institute. Attendee participation was encouraged and enhanced by panel discussions, break out sessions and roundtable discussions.

Th 2003 NRCEN workshop will be hosted by Anne Donnelly from the Engineering Research Center for Particle Science and Technology in Florida.

Liu Yen Kramer from UC Berkeley, stands ready to discuss her poster at the NRCEN poster session

Calendar of CfAO oriented Events

December 2002

Dec 2	Theme Leader outlines due for Year 5 Renewal Proposal
Dec 11	Executive Committee Teleconference
Dec 12-15	American Academy of Optometry Meeting

January 2003

Jan 5-9	201st Meeting of the AAS Seattle, WA
Jan 8	Executive Committee Teleconference
Jan 22	Executive Committee Teleconference
Jan 27-31	Globular Clusters: Formation, Evolution and the Role of Compact Objects, Santa Barbara, CA

February 2003

Feb 3	5 Year Renewal Proposal Due
Feb 5	Executive Committee Teleconference
Feb 19	Executive Committee Teleconference
Feb 13-18	AAAS Meeting Denver CO
Feb 22	1st Quarterly Report Due: November 2002, December 2002, January 2003

March 2003

Mar 1-3	Houston 50th Anniversary
Mar 5	Executive Committee Teleconference
Mar 12	Call for Keck Proposals
Mar 19	Executive Committee Teleconference
Mar 19	Call for Lick Proposals
Mar 20	Executive Committee Teleconference
Mar 20-23	**CfAO Spring Retreat 2003**
Mar 28-29	External Advisory Board Meeting

April 2003

Apr 2	Executive Committee Teleconference
Apr 3-8	B&L Meeting
Apr 16	Executive Committee Teleconference
Apr 15-17	5 Year Renewal Site Visit
Apr 22-25	Towards Other Earths-Darwin/TPF and the Search for Extrasolar Terrestrial Planets,Heidelberg, Germany
Apr 30	Executive Committee Teleconference

May 2003

May 1	Executive Committee Teleconference
May 4-9	Arvo (Vision Science), Fort Lauderdale, FL.
May 13-18	Grad/Postdoc Professional Development Workshop, Maui, HI
May 14	Executive Committee Teleconference
May 18-23	Applied Inverse Problems: Theoretical and Computational Aspects, UCLA Conf. Center, Lake Arrowhead CA
May 20 - 24	Internship orientation for undergrads working in Mauii
May 23	Year 5 Proposals are due
May 24-29	202nd Meeting of the AAS Nashville TN
May 28	Executive Committee Teleconferences
May 29	2st Quarterly Report Due: February , March , April 2003

June 2003

June 8-12	Future Directions in High Resolution Astronomy: A celebration of the 10th

Calendar of CfAO oriented Events

	Anniversary of the VLBA, Socorro, New Mexico
June 11	Executive Committee Teleconference
June 23-27	**CLEO Europe: Symposium on Adaptive Optics, Munich, Germany**
June 23-24	Proposal Review Committee Meeting (PRC)
June 25	Program Advisory Committee Meeting
June 29	**COSMOS, UCSC STARTS**
June 22-29	Internship Orientation, UCSC
June 25	Executive Committee Teleconference

July 2003

July 6-11	Gordon Research Conference on Origins of Solar Systems, Roger Williams College, Bristol, Rhode Island
July 9	Executive Committee Teleconference
July 13-26	XXVth International Astronomical Union General Assembly, Sydney, Australia
July 22-25	Star Formation at High Angular Resolution, Darling Harbor, Sydney, Australia
July 23	Executive Committee Teleconference
July 26	**COSMOS UCSC ENDS**

August 2003

Aug 2-5	Aberrations Meeting, Mopane, South Africa (Vision Science)
Aug 3-8	SPIE: 48th Annual Conference, San Diego CA
Aug 6	Executive Committee Teleconference
Aug 9-15	**Summer School on Adaptive Optics at UCSC**
Aug 9-12	CfAO Interns at UCSC
Aug 18-20	STC Directors Meeting at UCSC
Aug 20	Executive Committee Teleconference
Aug 29	3rd Quarterly Report Due: May, June, July 2003
Aug 28	Executive Committee Teleconference

September 2003

Sept 3	Executive Committee Teleconference
Sept 17	Executive Committee Teleconference

October 2003

Oct 1	Executive Committee Teleconference
Oct 5-9	OSA Annual Meeting, Tucson, AZ (Vision)
Oct 13-16	Multi-Wavelength Mapping of Galaxy Evolution, Venezia, Italy
Oct 15	Executive Committee Teleconference
Oct 29	Executive Committee Teleconference

November 2003

Nov 12	Executive Committee Teleconference
Nov 22	4th Quarterly Report: August, September, October, 2003
Nov 26	Executive Committee Teleconference

December 2003

Dec 4-7	Fall Science and Education Retreat
Dec 10	Executive Committee Teleconference ■

A Pictorial Record:
CfAO 2002 Fall Retreat, Lake Arrowhead, CA

Location: The UCLA Conference Center at Lake Arrowhead, California

Research Presentations

Breakout Sessions

A Pictorial Record (Continued)

Recharging the Educators

Preparing Demonstrations for the Industrial Participants Meeting

Fun and Games

Socializing

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."

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