Second Year Status Report for
The Laboratory for Adaptive Optics
UC Santa Cruz

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Executive Summary

The Laboratory for Adaptive Optics (LAO) has completed the second year of its six-year program to develop adaptive optics technology, concepts, and instruments for astronomy. The Gordon and Betty Moore Foundation initially funded the Laboratory in August 2002, with three main instrumentation thrusts: a Multiconjugate Adaptive Optics (MCAO) Laboratory; an Extreme Adaptive Optics (ExAO) Laboratory, and a Component Testing Laboratory. All three are aimed at improving the ability of ground-based astronomical telescopes to correct for the blurring due to the Earth's atmosphere, so that telescopes on the ground can make images as sharp as those in space.

During the first year we staffed the Laboratory and began preparing laboratory facilities. In the second year, we have made major progress in implementing our two main instrumentation thrusts, the multi-conjugate adaptive optics (MCAO) testbed and extreme adaptive optics (ExAO) instrument prototype, and began our third thrust, testing advanced components.

As of August 1, 2004, the LAO was fully staffed with two exceptions. The retirement of Gary Sommargren in May 2004 created an opening for a Laboratory Physicist and we are recruiting a second postgraduate researcher. In March 2004, we occupied Phase 1 of our newly renovated laboratory facility (approximately 650 sq ft). The remainder will be ready in February 2005. Our original plan was to have a fully available facility by November 2004. We moved the ExAO testbed from its temporary location in the Lick Observatory Optics Shops, and it is now up and running in the LAO. A second optical table is dedicated to testing MCAO components. Almost all of the major equipment for the ExAO prototype instrument and the MCAO testbed has been delivered and important experiments are underway. Below we will highlight the main technical milestones achieved.

The broader AO and astronomy community has twice shown its keen interest in the LAO in the past year. First of all, in December 2003, the Gordon and Betty Moore Foundation announced a $17.5M grant to the University of California to fund the conceptual design for a 30-meter telescope. This project is a partnership between UC and CalTech. LAO Co-Investigator Professor Jerry Nelson was named the Interim Project Scientist for the 30-meter telescope project (TMT), and LAO Director Donald Gavel was chosen as chairman of the Adaptive Optics Working Group. As a result, we anticipate a significant involvement of the Laboratory for Adaptive Optics in testing and verifying concepts for adaptive optics systems and components for the TMT. Second, in May 2004 the Associated Universities for Research in Astronomy (AURA) granted to a consortium of researchers led by LAO astronomer Bruce Macintosh a $230K design study contract for an extreme adaptive optics planet imager coronagraph (EXAOC) for the 8-meter Gemini National Telescope. This study contract will position the LAO to compete with one other group for the construction of the ExAO instrument at an estimated $14M.

In addition, the National Science Foundation's Adaptive Optics Development Program (AODP), administered by the National Optical Astronomical Observatories (NOAO), initiated research programs on advanced deformable mirrors, wavefront sensors, lasers, and computer algorithms for adaptive optics. Three of the six funded projects under this program will include LAO participation in testing prototype components.

The Laboratory is clearly on the way to achieving its goal of providing a venue that serves a national community, provides key facilities for future giant telescope projects, and trains the next generation of leaders in adaptive optics hardware and software systems.

Second Year Status Report

Staffing

The LAO staff comprises Principal Investigator Claire Max, Co-Investigators Jerry Nelson and Joseph Miller, Laboratory Director Donald Gavel, four senior researchers, a postdoctoral researcher, a graduate student researcher, a laser/optics engineer, a computer hardware/software engineer, an administrative assistant, and business services support from the UCO/Lick Observatory Business Office.

One new graduate student researcher will join the LAO in the fall of 2004, and an additional postdoctoral research fellow is being recruited.

The four senior LAO researchers are Bruce Macintosh, astronomer and chief scientist for the EXAOC project; Gary Sommargren, an expert in ultra-precise metrology, who provided the metrology expertise on the XAOPI project; Brian Bauman, an optical engineer experienced in adaptive optics, is leading the optics engineering efforts for both the EXAOC and MCAO projects; David Palmer, who is consulting with us on computer control and is program manager for the Gemini ExAOC project. As we mentioned earlier, Sommargren retired in May 2004 so his position is now open. All four senior LAO researchers were on multi-location appointment (MLA) from the Lawrence Livermore National Laboratory (LLNL), which is managed by the University of California, and spent approximately half of their time at LAO.

The LAO has funding allocated for two postdoctoral researchers. One of these positions has been filled by Renate Kupke (University of Hawaii), an astronomer with a background in adaptive optics gained while working on wavefront sensor modeling and development with one of the pioneers in the field, François Rodier. The second LAO position is currently under recruitment.

This past year, three graduate student researchers (GSRs) worked with the LAO, two of whom provided their own funding. Supported by his own NSF Fellowship in his first year as an Astronomy graduate student, Mark Ammons, assembled a single-conjugate, adaptive optics system. This system will serve as both an educational demonstration and a research testbed for cases not needing full MCAO capability. While still an undergraduate, Ammons built his own adaptive optics system. He elected to pursue his graduate degree at UC Santa Cruz specifically because of the opportunity to work at the LAO and in the Center for Adaptive Optics. The second GSR, Zhenrong Wang, graduated from UCSC in June 2004 with a Master’s degree in Electrical Engineering. He completed the assembly and calibration of a specialized interferometer for testing the spatial light modulators to be used in the MCAO testbed. With Wang’s graduation, we have identified an incoming Astronomy graduate student, Jess Johnson, to fill this position starting in September 2004. The third graduate student, Julia Wilhelmson (UC Davis), is doing her PhD research in the LAO’s Extreme Adaptive Optics lab facility. Wilhelmson also brings her own financial support.

In addition to the academic appointments, the LAO has hired a senior laser/optics assistant engineer and a computer hardware/software engineer. The laser/optics assistant engineer, Daren Dillon, started in September 2003, and has been a wonderful addition to our staff.

His presence greatly sped up implementation of a working laboratory. Dillon comes with extensive laser electro-optic technician experience (at both the Los Alamos and LLNL) and had valuable prior experience working with Gary Sommargren at LLNL in the Extreme Ultraviolet Lithography (EUL) program. The EUL program required developing the exquisitely precise metrology technology now being used in the LAO's ExAO testbed. The computer hardware/software engineer, Marc Reinig, came to the LAO in January 2004, and immediately kicked off an effort to configure the MCAO system hardware and electronics. Reinig has broad industrial experience, including several years as an independent consultant in high-speed interfaces between electronics and computer equipment. The LAO has a part-time Administrative Assistant shared with the CfAO, Cherilin Stephens. The UCO/Lick Business Office provides support in the areas of financial analysis, purchasing, human resources, payroll and facilities administration. Finally, UCO/Lick technical shops provide additional technical support as needed. This past year, they provided services in mechanical engineering, electronics, optics and machining.

In summary, the LAO has filled its academic research, technical support, and administrative positions minus one postdoctoral researcher and the replacement senior researcher.

Facilities

Phase 1 of the 1900 sq. ft. on the first floor of the Thimann Laboratories building is completed (Figure 1), with about 650 sq. ft. now occupied with ongoing experiments. This location has the advantage of being close to the UCO/Lick Observatory facilities and to the Center for Adaptive Optics (CfAO). The ground floor location makes it suitable for maintaining the temperature and vibration control necessary for the precise optical measurements performed in the LAO.

Figure 1. Moving in to the Phase 1 facility in Room 191 of Thimann Laboratories. Left: (April 2004) the two honeycomb steel optical tables, with a light enclosure under construction on one table and various optical components being set up. Right: (July 2004) the ExAO experiment's PSDI interferometer within its enclosure on the left table and MCAO testbed area on the right. The MCAO table contains the Quadrature Polarization Interferometer for qualifying and characterizing the spatial light modulators and a general-purpose commercial Fizeau interferometer for optical measurement of MEMS devices and other optical components.

For Phases 2 and 3 we continue to work with the architect, Glass Associates of Oakland, who has retained an experienced laboratory facilities consultant, Thomas Mistretta

(Research Facilities Design), to assist in the detailed laboratory planning. Glass Associates, in conjunction with the UCSC architect, is monitoring this project to completion. As mentioned in last year's report, the renovation in Thimann Labs is occurring in three phases. This schedule has allowed us to utilize some space more quickly while phasing the more complicated and time-consuming construction.

Phase 1 included an expedient refurbishment of the floor and walls in Room 191 and the addition of two double doors (Figure 2). This work was finished in March 2004. Two 16-foot honeycomb steel optical tables now accommodate the first extreme adaptive optics (ExAO) and multi-conjugate adaptive optics (MCAO) experiments.

Phase 2 consists of converting Room 185 from a classroom to an optics laboratory. The Room 185 conversion is now scheduled for occupancy in November 2004.

Phase 3 consists of completing the renovation of Room 191, when 191 B and C become available for LAO use in the fall of 2004. Experiments in 191 will be moved to Room 185 during this time. When the renovation in Room 191 is complete (projected in February

Figure 2. Laboratory for Adaptive Optics Facility Plan. Phase 1, partial refurbishment of Room 191 (completed in March 2004). The ExAO and MCAO experiments now share this space on two honeycomb steel optical tables. Phase 2, refurbishment of Room 185, scheduled to be complete in October 2004, at which time both experiments will be moved there. At the completion of Phase 3, in February 2005, MCAO will inherit the two steel optical tables and the ExAO testbed will move to Room 191 onto a granite optical table. Phase 1 is interim, with only moderate temperature and lighting control. Phases 2 and 3 will have precise temperature, lighting, humidity, and dust control.

2005) the ExAO experiment will be relocated into Room 191 and the MCAO experiment will remain in Room 185. The 18-foot granite optical table will be moved from the Lick Optical Shops and put into Room 191 for ExAO instrument prototyping. The two steel optical tables will remain in 185 to serve the MCAO experiments.

Phases 2 and 3 involve significant changes to the air conditioning and vibration environment, including isolating the building AC fans. Recently, we added a maximum humidity specification to accommodate the ExAO MEMS deformable mirrors. Tests at our interim facility at the Lick optical shops revealed that some of the microfabrication layers were subject to unexpected deterioration at conditions of high voltage and high humidity. Subsequent tests by the MEMS manufacturer at their facility isolated the problem, which is now being temporarily addressed by a hermetic seal and optical window. The additional requirement for humidity control in the laboratory is a relatively straightforward modification and will not significantly affect our schedule. This change-order will incur approximately $12K more in construction costs.

Experiment Results: ExAO

The ExAO system, whose goal is to image extrasolar planets, will take advantage of the large number of actuators available on a MEMS deformable mirror to achieve high-contrast imaging of stars and their surrounding planetary systems[1]. Here is a list of milestones completed to date:

The XAOPI prototype effort has moved from its temporary facility at the Lick optical shops to the LAO lab in Thimann Laboratories.

The second version of the Phase-Shifting Diffraction Interferometer (PSDI) was completed and subsequent testing proved it capable of measuring wavefronts down to the 1 nm rms level. Using a specially designed diffraction-controlling pupil mask we independently verified the 1 nm wavefront quality by measuring 10^{-7} contrast levels in far-field images (Figure 3).

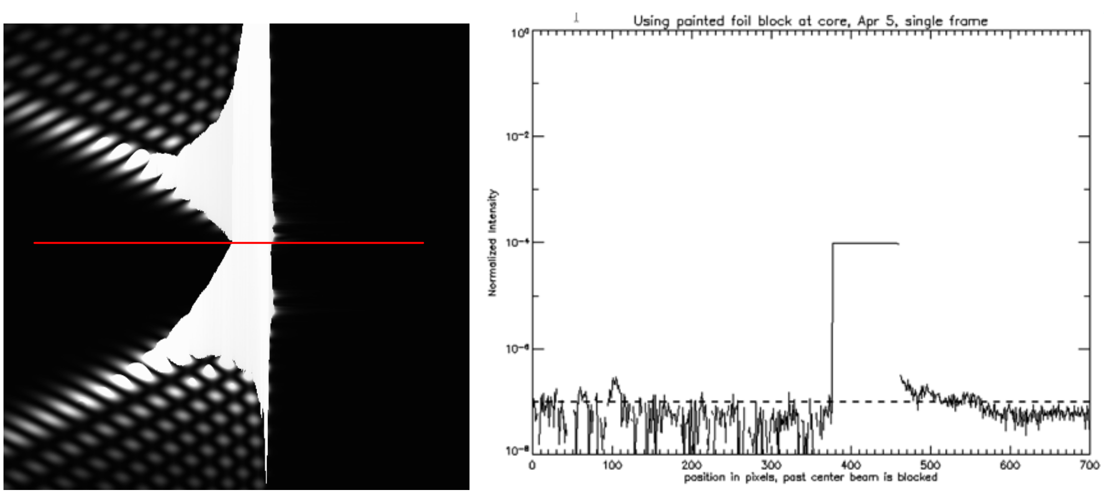

Figure 3. High-contrast far-field imaging tests of wavefronts from the Phase-Shifting Diffraction Interferometer. With a specially shaped pupil mask, coherent diffracted light is scattered in preferential directions, leaving a wedge shaped dark area (to the left in the left image). The light from the central star is mostly blocked on the right by a knife edge in front of the camera. Any imperfections in the interferometer optics would scatter light into the dark region. However careful photometric analysis of the camera images reveals that the dark region contrasts with the central star by at least a factor of 10^7 (graph of log-intensity vs position shown on the right). This is the contrast measurement needed to assure that XAOPI will be able to detect planets.

The Boston Micromachines Corporation has provided a number of one-thousand-actuator MEMS deformable mirrors under their development contract with LAO. In the latest series of experiments we were able to flatten the mirror surface to 2.5 nm rms, which is unprecedented quality for any deformable mirror. Figure 4 shows a grey-scale rendition of the residual surface error as measured by the PSDI.

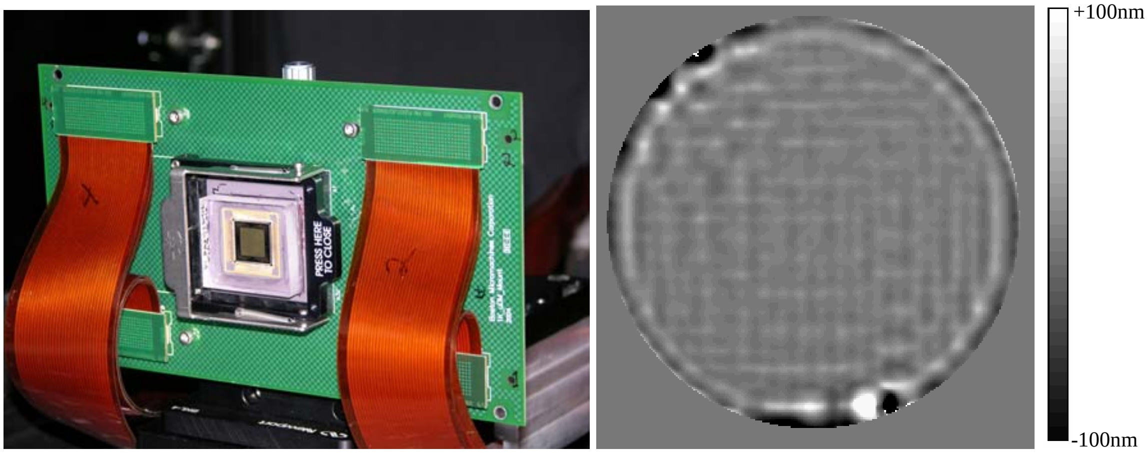

Figure 4. Left: the MEMS deformable mirror is shown in its mount.Right: grey-scale display of wavefront phase, as measured by PSDI, of a 9-mm diameter circular beam of light reflected off the central area of the MEMS. The MEMS device has a 10-mm square active area. An iterative algorithm using PSDI measuremen`ts determines the voltage commands required to achieve maximum flatness. Residual wavefront error, on the order of 5 nm rms, is mostly “print-through” of actuator mounting structure to the continuous mirror surface.

AURA has funded a design study, headed by Bruce Macintosh, for an Extreme Adaptive Optics Coronagraph (EXAOC) instrument for the 8-meter Gemini telescope. LAO will help design and test the prototype instrument, and if the contract is awarded, will be the site for the instrument fabrication and testing. Figure 5 shows a computer simulation of the performance of this system.

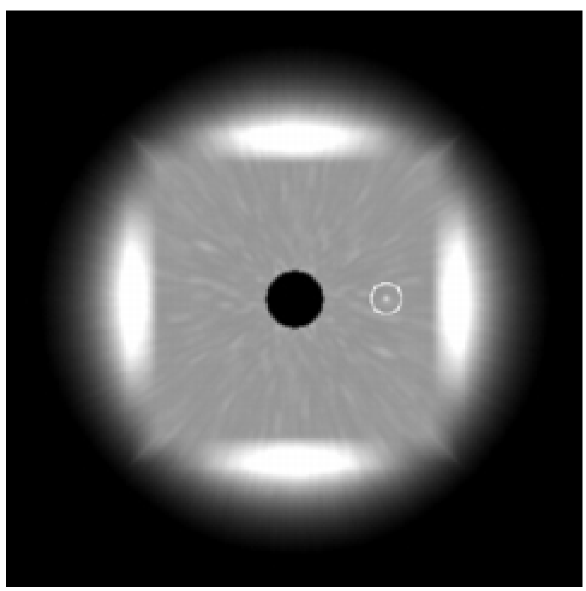

Figure 5. Output from a simulation of the ExAO planet imager being designed at the LAO. Wavefront control using the deformable mirror carves out a dark square region around the central star: the “discovery space.” Light from the central star is blocked by a coronagraph (black spot) and an apodizing Lyot stop (in this example) suppresses diffraction. The faint detected planet, a 1-million year old “warm Jupiter” still glowing under its own heat of formation, is shown circled in white on the right. Streaks are residual speckles from calibration imperfections allowed in the instrument error budget.

Experiment Results: MCAO

Multi-conjugate adaptive optics (MCAO), or more broadly, multiple-laser guidestar tomography for AO-corrected wide-field imaging, is intended to enable diffraction-limited imaging using the “Extremely large” (>30-meter class) telescopes of the future. The MCAO test bench is coming together with a complete optical design, initial components delivered, and component characterization in progress. In addition, LAO is developing innovative adaptive optics system concepts development in the areas of wavefront sensing and optimal control in separate experiments.

Optical design and component layout. To perform laboratory experiments relevant to MCAO on a 30-m telescope, one must scale 60 km of turbulent atmosphere and a 30-meter diameter telescope to fit on a room-size optical bench, while still retaining the proper diffractive behavior of the optical system. This scaling consideration has driven the optical design and layout of the testbed. The scaling issues and their resolution are summarized in a report to the LAO/CfAO community[2]. The testbed optical design was completed and all critical components have been delivered. In December 2003, our optical engineer, Brian Baumann, completed his PhD thesis on the optical design of AO systems for extremely large telescopes[3].

Component characterization. Some components are new technology and need to be characterized, particularly the spatial light modulators used as “surrogate” deformable mirrors. The deformable mirrors required for a 30-meter telescope AO system need many more actuators than are currently available DMs. Therefore we opted to use the Hamamatsu liquid crystal spatial light modulator (SLM) as a surrogate for our laboratory experiments. This device controls the optical phase with 768 x 768 pixel resolution, and thus can easily emulate the 10,000 actuator DMs that would be needed on a 30-meter telescope. The Hamamatsu SLMs only work with polarized, monochromatic light, and thus are unsuitable for astronomy, but are completely adequate for laboratory testing of AO wavefront control.

A test interferometer for the SLMs, the Quadrature Phase Interferometer (QPI), was set up in the LAO to test and calibrate the first SLM before purchasing an additional 3 SLMs from Hamamatsu. These additional SLMs have now arrived and we are using the QPI to characterize them. Zhenrong Wang, an electrical engineering graduate student, did the work and wrote his master’s thesis on the instrument[4] (Figure 6).

Atmospheric aberration plates. Mimicking a turbulent atmosphere in the laboratory requires a means of creating optical aberrations similar to those of the Earth’s atmosphere. Under the guidance of the LAO, the microfabrication facility at LLNL is fabricating glass plates that simulate atmospheric aberrations. The challenge is to achieve a high dynamic range of optical path difference to simulate the atmosphere over a 30-meter telescope aperture with a total of about 20 µ of optical path variation, to on-the-order-of 100 nm precision, which is the adaptive optics correction accuracy goal for MCAO on a 30-m telescope. The first set of plates has been delivered (Figure 7).

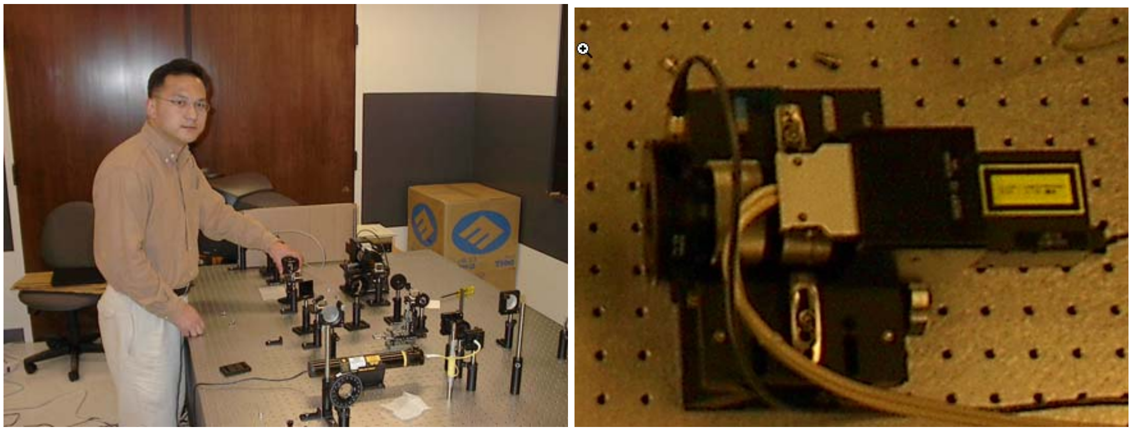

Figure 6. Left: EE Master's student Zhenrong Wang aligning the quadrature phase interferometer. Right: the liquid crystal spatial light modulator.

A vendor's initial experiments with low-cost epoxy-replication of the glass plates have failed. Rather than spend time developing this approach, we are proceeding with the fabrication of additional glass plates at the LLNL etching facility. By changing the etch depths we will simulate atmospheric layers with various turbulence strengths.

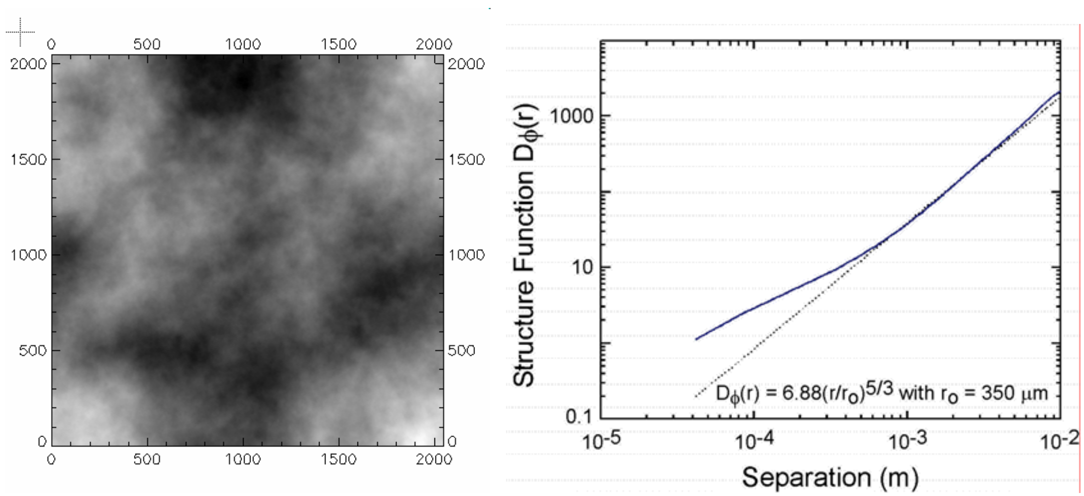

Figure 7. Atmospheric turbulence phase plate. Left: the grey scale indicates the degree of optical path length change caused by the etched plate as a function of position on the plate. The plate is 100 mm square. The plate was measured using an interferometer at LLNL. From this measurement data, the plate's actual spatial structure function, shown of the right with a solid curve, is compared to the theoretical Kolmogorov structure function expected in the atmosphere (dashed line).We are working with LLNL to improve the match at short spatial scales (<1mm). The present plate is perfectly adequate for initial testing.

Algorithm development. Major progress has been made on the tomography algorithms needed to command multiple deformable mirrors, given measurements from multiple laser guide stars. This work was done in collaboration with members of the Center for Adaptive Optics within its Adaptive Optics for Extremely Large Telescopes CfAO theme area. LAO Director Donald Gavel presented a paper at the 2004 SPIE conference deriving the real-time minimum-variance control algorithm for laser guidestar MCAO and showed that its structure is similar to cone-beam back-projection algorithms used in medical tomography[5].

Single conjugate AO testbed. A stand-alone single deformable mirror adaptive optics system was constructed by graduate student Mark Ammons. This system uses a membrane type MEMS deformable mirror built by Intellite Corporation. Ammons wrote the basic control software and user interface, and recently used the system for a closed loop system demonstration at the CfAO summer school.

The single conjugate system will be used to develop algorithms and system concepts that do not necessarily need to tie up the entire MCAO testbed. For example, there is ongoing theoretical work within the CfAO to develop Strehl-optimizing and wind-predictive control algorithms[6]. The single conjugate system will provide the laboratory testbed for evaluating these concepts.

Summary

The Laboratory for Adaptive Optics is progressing toward each of its three main goals. We have attained major experimental milestones in establishing the feasibility of an "extreme" adaptive optics instrument for planet imaging. We have made substantial progress in establishing a testbed for a wide-field tomographic adaptive optics system for MCAO. And we are actively testing key components for future AO systems. We have been able to hire outstanding staff, and we are well along in the process of preparing experiments in the permanent laboratory space of the LAO. A staged plan of lab space refurbishment has allowed us to begin our initial experiments in a timely manner.

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