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

Submitted to the
Gordon and Betty Moore Foundation

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Executive Summary

The Laboratory for Adaptive Optics (LAO) has completed the third 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 diffraction-limited images as clear as those in space.

This is a summary of the milestones achieved in year three:

- The new laboratory facilities in Thimann Sciences Building are complete and our experiments are moved in to their permanent locations. In May, 2005 we hosted Moore Foundation President Ed Penhoet and Trustee Kenneth Moore at a laboratory dedication ceremony and tour.
- The Gemini Observatory has selected the team led by Bruce Macintosh to build the Extreme Adaptive Optics Coronagraph, an instrument that will image and characterize planets outside our own solar system. Initial experiments at the LAO led to a successful proposal for this $22M instrument. The ExAOC will be prototyped, assembled, and tested at the LAO over the next few years. This is a major step in accomplishing one of the main missions of the LAO: to build an adaptive optics instrument to go on an existing ground based telescope that will find and characterize extrasolar planets.
- We have made considerable progress in developing advanced adaptive optics (AO) concepts for the next generation of extremely large aperture telescopes and in testing component technologies for these systems. The MCAO prototype instrument is near completion of its assembly and test phase. A new system concept, Multi-Object Adaptive Optics (MOAO) has emerged over the past year through the work of Donald Gavel at the LAO and others involved with the Thirty Meter Telescope project. MOAO provides an extremely wide field of AO correction that is ideally suited to multi-object spectrographs – a mainstay for science programs on extremely large telescopes. The MCAO prototype testbed has now been redesigned to allow switching between MCAO and MOAO configurations.
- The LAO has hosted a number of visitors and students from industry, academia, and summer programs at UCSC. High school students from the Center for Talented Youth, studying physics and astronomy for the summer, toured the laboratory in July. We hosted and gave experiment demonstrations to graduate students and researchers attending the Center for Adaptive Optics Summer School for Adaptive Optics in August.

The LAO is now staffed with two full-time research scientists, two full-time engineers, one postdoctoral researcher, and four graduate students, plus three half-time consulting scientists from Lawrence Livermore National Laboratory. We have openings (and have recently interviewed candidates) for two more postdoctoral researcher positions.

The broader AO and astronomy community has shown its keen interest in the LAO during the past two years. 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. LAO co-Investigator Professor Jerry Nelson is now the Project Scientist for the 30-meter telescope project, and LAO Director Dr. Donald Gavel served as chairman of the Adaptive Optics Working Group and is now PI for the multi-object adaptive optics (MOAO) instrument feasibility study. We anticipate an ongoing involvement of the Laboratory for Adaptive Optics in testing and verifying concepts for adaptive optics systems and components for the 30-meter telescope. 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. In August 2005 the Gemini board announced the selection of Dr. Macintosh's team for the construction of the ExAO instrument at an estimated overall budget of >$20M.

The National Science Foundation's Adaptive Optics Development Program (AODP), administered by the National Optical Astronomy Observatory (NOAO), despite cutbacks this year that curtail starting any new programs, continues to support ongoing multi-year 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 through forefront laboratory research in adaptive optics, provides key facilities for future giant telescope projects, and trains the next generation of leaders in adaptive optics hardware and software systems.

Third Year Status Report

Research Facilities

The third and final phase of the 1900 square foot refurbishment of laboratories on the first floor of the Thimann building is now complete (Figure 1), with experimental testbeds in their permanent locations. This Thimann location is close to the UCO/Lick Observatory facilities, the UCSC Astronomy Department, and the Center for Adaptive Optics (CfAO) on science hill on the UCSC campus. The laboratory facility is designed to maintain a controlled temperature, dust, lighting, humidity, and vibration environment, which are crucial for the precise optical measurements performed there. The new facility includes a 200 square foot class 100 clean room which will enable ultra-clean assembly of the final optical cells in a planet imaging instrument plus provide an environment for any other testing where scattered light from dust particles must be kept to a minimum.

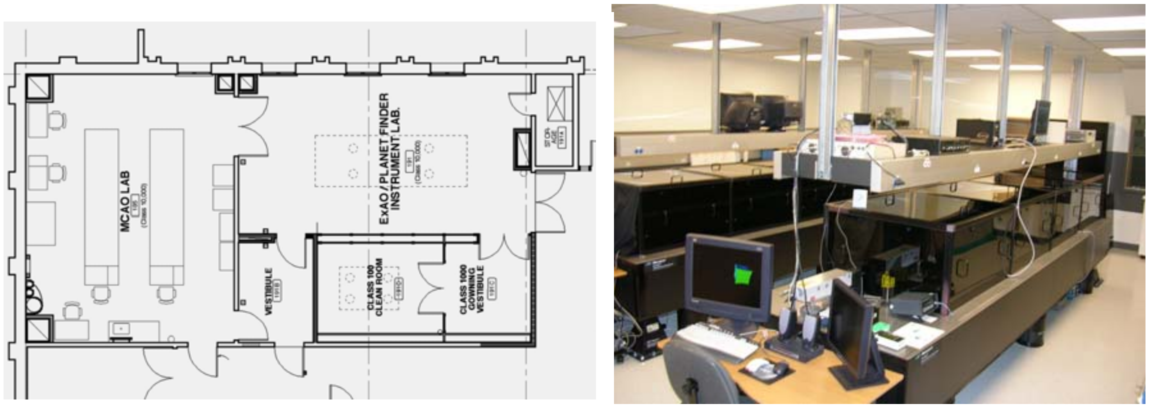

Figure 1. Laboratory for Adaptive Optics

In room 185, two large optical tables now accommodate the multi-conjugate/multi-object adaptive optics (MCAO/MOAO) testbed and other experiments related to the AO for next generation extremely large telescopes mission. A bird's eye view layout of the MCAO/MOAO testbed is shown in Figure 2.

A third, smaller, table contains a commercial general purpose optical testing interferometer which is used to measure large optical components as well as small devices such as micro electro-mechanical systems (MEMS) deformable mirrors. A second interferometer, which we designed specifically for our testing purposes, takes interferograms at high speed to characterize the time response characteristics of adaptive optics devices. We are awaiting delivery of a differential image contrast microscope with precision metrology that will enable us to evaluate the fabrication quality of MEMS devices, coronagraphic masks, spatial filters, and optical slicer elements used in wavefront sensors.

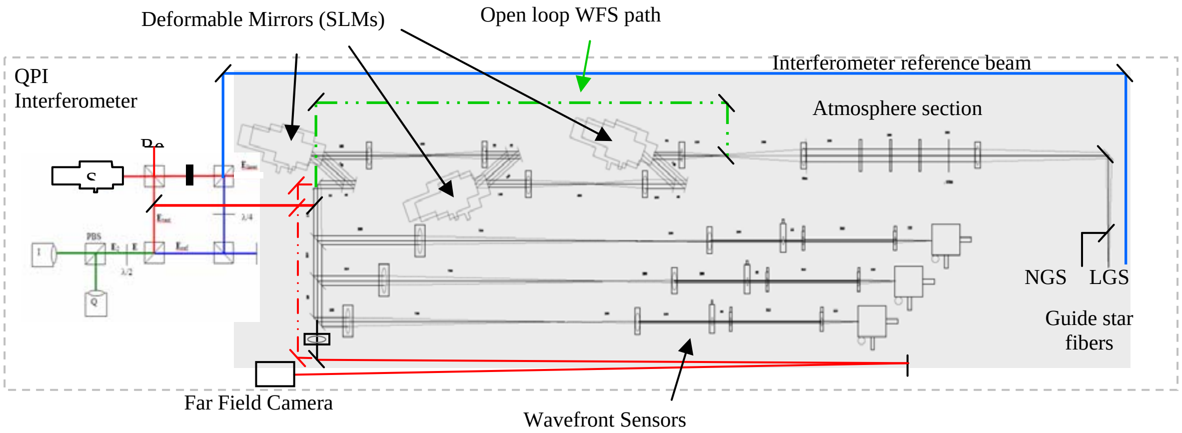

Figure 2. MCAO/MOAO Testbed

In room 191, an 18-foot long granite optical table accommodates the ExAO testbed with its point-diffraction interferometer. The granite slab, donated by Lawrence Livermore National Laboratory, provides extra stability and vibration dampening.

Next to the ExAO testbed is the entrance to the class 100 clean room. The layout anticipates the workflow during assembly and integrated testing of the Extreme Adaptive Optics planet imager/Coronagraph (ExAOC) instrument.

Each of the laboratory rooms has additional lab benches for assembly and testing of electronics.

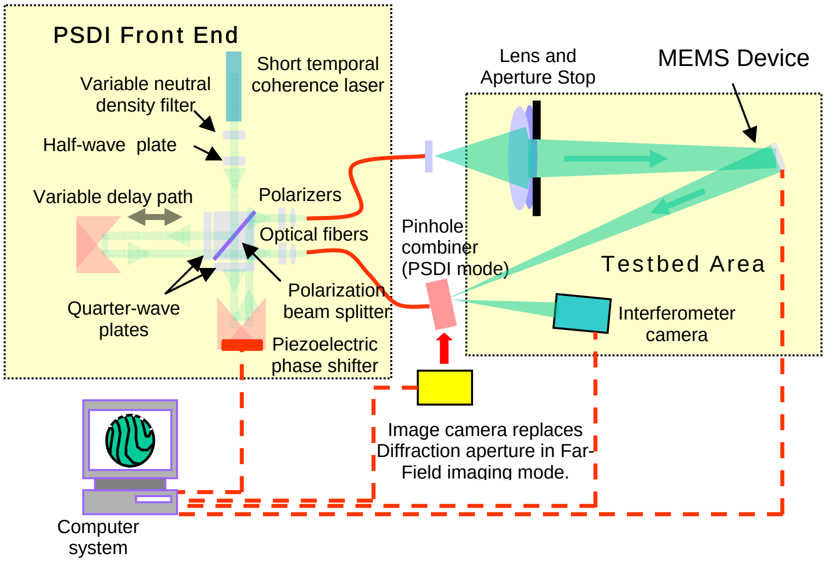

Figure 3. ExAO Testbed

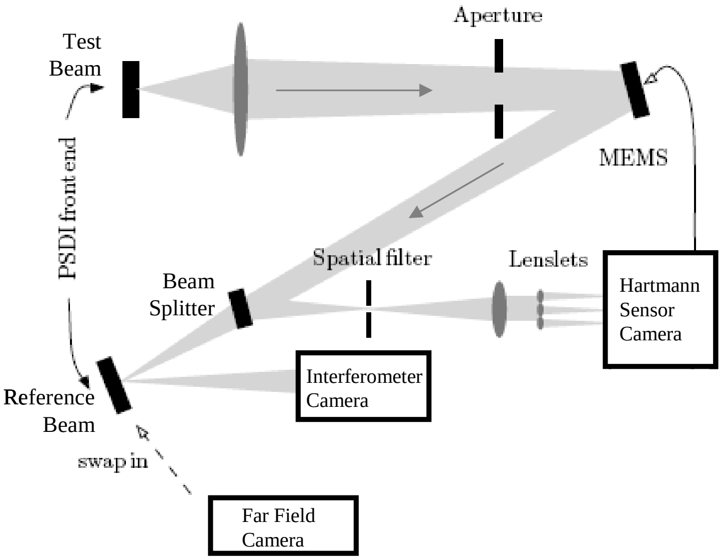

Figure 4. Modified ExAO testbed layout showing the incorporation of a Hartmann sensor

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 accomplished in year 3:

- The Phase-Shifting Diffraction Interferometer (PSDI) has proven capable of measuring wavefronts down to 0.3 nm rms accuracy. Our long-term stability measurements show that it is able to hold this accuracy for an hour.
- A MEMS deformable mirror has been controlled to a flatness of less than 1 nm rms and has generated a high contrast ($<10^{-6}$) far-field image.
- The MEMS deformable mirror has been controlled to “undo” the aberrations of a test aberrator plate down to less than 3 nm wavefront error.
- A Hartmann wavefront sensor was added to the ExAO testbed and tested. The Hartmann sensor is necessary in the fielded astronomical instrument in order to sense the wavefront from incoherent starlight. We’ve proven the Hartmann sensor to agree with the PSDI to about the 2.2 nm level and we are working to characterize, quantify, and eliminate sources of systematic and random error.
- A new concept for precise Hartmann wavefront sensing without aliasing error was developed by Bruce Macintosh and Lisa Poyneer[2]. This was tested and proven for the first time in the laboratory (Figure 5).
- The team led by LAO researcher Bruce Macintosh has been selected to build the Extreme Adaptive Optics Coronagraph (ExAOC) for the Gemini Observatory. ExAOC will be prototyped, assembled, and tested at the LAO over the next few years.

PSDI stability

The ExAO testbed, comprised principally of the PSDI interferometer, was moved from a Newport steel optical table to the donated granite optical table when the refurbishment of the room 191 laboratory was completed in May of this year. We have long term stability of measurements taken with the PSDI looking at a reference flat mirror in the place of the MEMS device on both tables. A large part of the systematic error was traced to a slowly varying spherical aberration that was attributed to very slight temperature variations in the room air affecting the overall optical path differences in the interferometer. After averaging this out, we obtain very repeatable measurements of wavefront, down to 0.3 nm rms over an hour.

MEMS device characterization

We continue to receive new MEMS deformable mirror devices from Boston Micromachines Corporation under a two-year development contract.

The main issue with the 1000 actuator device as it impacts ExAO is actuator yield, the i.e. percentage of working actuators. On a good device that we have (taken from the most recent MEMS fabrication run) most actuators are working well, having excellent (within 0.4nm) repeatability and full range of operation (about 1 micron surface displacement). The bad actuators have been categorized according to their (mis)behavior in an attempt to work with Boston Micromachines to determine and mitigate the cause. A variety of problems can occur, for example, broken mechanism, broken or shorted conductive paths in the device, broken wire bond in the packaging, or misbehaving channel in the drive electronics, all of which we are exploring in tests. The goal for ExAO is to achieve less than 0.5% failed actuators on average.

Wavefront control experiments

Three types of successively more complex MEMS wavefront control experiments were performed to establish the capability of the system as a whole:

1) Flatten the MEMS surface to high accuracy

2) Measure an aberrated wavefront interferometrically and control the MEMS to flatten the wavefront to high accuracy

3) Measure the aberrated wavefront using a Hartmann sensor and control the MEMS to flatten the wavefront to high accuracy.

So far, we are approaching but have not yet achieved the goal for ExAOC: a 1 nm rms total wavefront error budget, but we are close. Ongoing experiments are continuing to uncover additional sources of small error.

A key metric of system performance is how well, in the final image, scattered light from the star is kept away from a “discovery” region around the star where we want to detect planets.

In order to improve on theoretical performance with the Hartmann wavefront sensor, Bruce Macintosh and Lisa Poyneer developed a novel addition, a sharp mask (spatial filter) that is placed at the focus ahead of the Hartmann sensor. This mask effectively eliminates a type of wavefront error induced by Hartmann sensing that tends to move light, which otherwise would have scattered out of the planet discovery region near the parent star, back into the discovery region, thus obscuring the planet. The theory of operation of the spatially filtered wavefront sensor was worked out by Lisa Poyneeer[2], and was tested recently for the first time on the ExAO testbed. The results (Figure 5) show evidence of preserving the darkness of the discovery region.

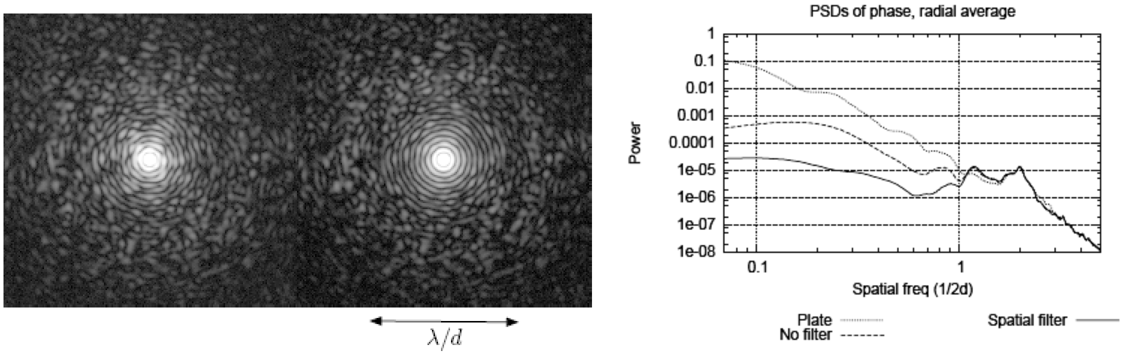

Figure 5. ExAO far-field image results with and without the Poyneer/Macintosh spatial filter modification to the Hartmann sensor. Closed loop correction of the phase aberration from a test aberrator plate is shown without [left] and with [right] the spatial filter. The improvement in correction which occurs in the λ/*d* central area manifests as much darker nulls between the Airy diffraction rings. When a coronagraph is imployed (in the next stage of development of the ExAO testbed) the diffraction rings will be suppressed, leaving the discovery region dark enough to image the planet. The graph on the right shows quantitatively how flux energy is reduced in the controlled region.

In last year's report we showed how, with a reference flat in the MEMS position and using a specially shaped pupil mask designed to suppress diffraction, we could produce a far field image with a dark discovery region with better than 10^{-7} contrast. We have now controlled the MEMS to nearly this level of accuracy[3]. Figure 6 shows a lineout through a far-field measurement.

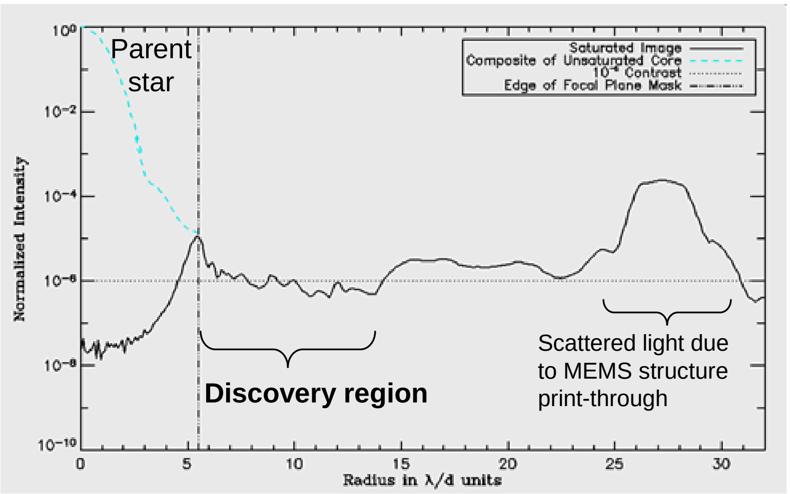

Figure 6. Far-field contrast with the MEMS device flattened to ~<1 nm rms in its controlled spatial frequency band and the shaped pupil mask used to suppress diffraction. The dark hole (discovery region) extends to 14 λ/d. From 6-10 λ/D the average contrast is 1.21 x 10^{-6}, in the 7-14 λ/D range contrast is 7.89 x 10^{-7}.

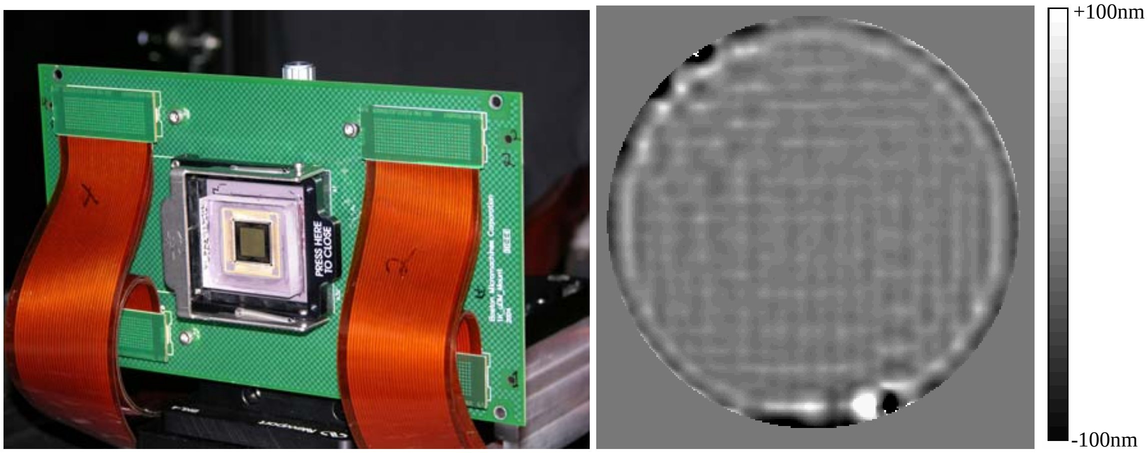

Figure 7. Left: the MEMS deformable mirror is shown in its mount. Right: grey-scale display of wavefront phase, as measured by PSDI, of a 9-mm diameter circular beam of light reflected off the central area of the MEMS. The MEMS device has a 10-mm square active area. An iterative algorithm using PSDI measurements determines the voltage commands required to achieve maximum flatness. The residual wavefront error visible, on the order of 5 nm rms, is mostly “print-through” of actuator mounting structure to the continuous mirror surface. This high spatial frequency ripple scatters light mostly outside of the discovery region in the final image.

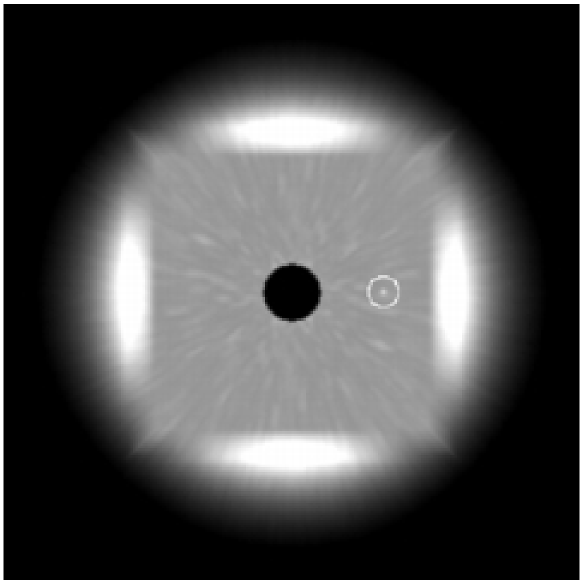

Figure 8. Simulation of the ExAO planet image using the ExAO Coronagraph instrument. Wavefront control by the deformable mirror carves out a dark square planet discovery region around the central star. Light from the central star is blocked by a coronagraph (black spot) and an apodizing Lyot stop suppresses 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 imaging, is intended to enable wide-field diffraction-limited imaging using the “Extremely large” (>30-meter class) telescopes of the future. The test bench is nearing its completion with full system characterization experiments slated to start in September. Individual components including the spatial light modulator deformable mirrors, Hartmann wavefront sensors, and phase aberration plates have been fully characterized. In parallel, LAO is pursuing innovative adaptive optics system concepts in the areas of wavefront sensing and optimal wavefront control in separate experiments.

MCAO testbed 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.

Optical path – MCAO mode

The MCAO optical testbed layout is shown in Figure 2. Light enters the system via laser fibers emulating the guide stars, labeled NGS (natural guide star) and LGS (laser guide star) at the lower right of the figure. Here there is an array of sources to simulate a multi-guidestar constellation, plus one deployable source to simulate science objects at arbitrary locations in the field. The guide star and science object light travels through a series of phase aberration plates in the atmosphere section, to emulate multiple layers of air turbulence at different altitudes in the atmosphere. At this point the light is focused, as it would be in an actual telescope, then fed to a series of deformable mirrors (we are using liquid crystal spatial light modulators to perform the function of deformable mirrors). From there, the AO corrected light is sent to a number of Hartmann wavefront sensors, each of which senses an individual guide star. The AO corrected light also travels to a far-field imaging camera to characterize Strehl ratio and other performance metrics of the corrected imaging. Another path goes to an interferometer to characterize AO corrected wavefront quality.

We mentioned this interferometer earlier as one that takes interferograms at high speed. The MCAO testbed is designed to run in “closed loop” at a relatively quick pace while the phase aberration plates are moved to simulate wind blown turbulence. This allows us to characterize the dynamic behavior of MCAO control algorithms.

MOAO mode

The MCAO arrangement on the optical bench can be conveniently switched to an MOAO configuration (the green dotted line path in Figure 2). In MOAO mode, each science object has its own dedicated deformable mirror, so the AO correction is specific to and optimized for the direction the science light comes from. Guide star light is steered to the wavefront sensors directly, without bouncing off any deformable mirrors, where it is detected and processed to form a model of the entire volume of atmosphere.

The MOAO system runs in "open loop," that is, the effect of AO commands to deformable mirrors are not sensed by the wavefront sensors. This puts additional demands on deformable mirror technology to respond accurately to commands without having to be re-measured. Tests designed to measure this property of MEMS deformable mirrors are ongoing in the PSDI interferometer.

Component characterization. Some components used in the MCAO/MOAO testbed are new technology and need to be tested and characterized. In particular we spent some time calibrating the spatial light modulators. The deformable mirrors (DMs) required for a 30-meter telescope AO system need many more actuators than are available on currently available DMs. Therefore we opted to use a liquid crystal spatial light modulator (SLM) manufactured by Hamamatsu Corporation as a surrogate deformable in our laboratory experiments This device controls the optical phase with 768 x 768 pixel resolution, and thus can easily emulate the 10,000 actuator deformable mirrors 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 three SLMs from Hamamatsu. We have now completed the following characterizations on all four devices:

- Departure from response linearity: Phase versus applied command signal, over the 0-2π dynamic range of the device
- Departure from spatial uniformity: The above phase versus applied command signal curves, as a function of spatial location on the device
- Speed of response

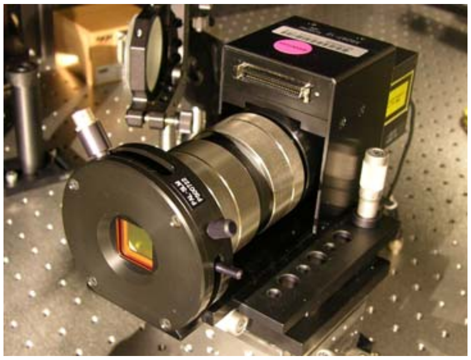

Figure 9. This liquid crystal spatial light modulator (SLM) acts like a deformable mirror with the polarized laser light used on the MCAO testbed. Its 768x768 pixilated array can be used to emulate any of the candidate astronomy deformable mirrors

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. By etching away various amounts of glass from initially flat plates, an arbitrary pattern of optical phase aberrations can be created. Five glass plates that simulate the Kolmogorov statistical pattern of atmospheric aberration were delivered to LAO this year. The plates will be positioned in the atmosphere section of the testbed to simulate layers of turbulence at various altitudes.

We have successfully measured these plates optically in the Quadrature Polarization Interferometer (the one used on the MCAO testbed), in the Point Diffraction Interferometer (the one used on the ExAO testbed), and in Hartmann sensors on both testbeds (Figure 10), proving that they are suitable for use in all our AO system experiments.

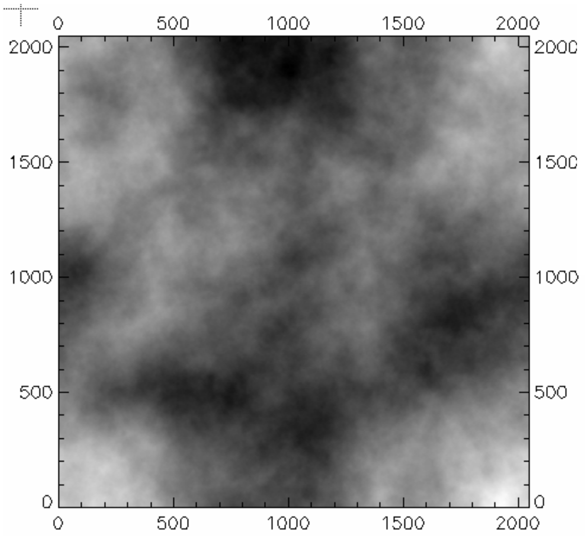

Figure 10a. Sample atmospheric turbulence pattern used to generate phase plates for the lab. The grey scale bitmap file used to generate etch masks to make the plates. Brightness indicates the degree of phase change as a function of position on the plate.

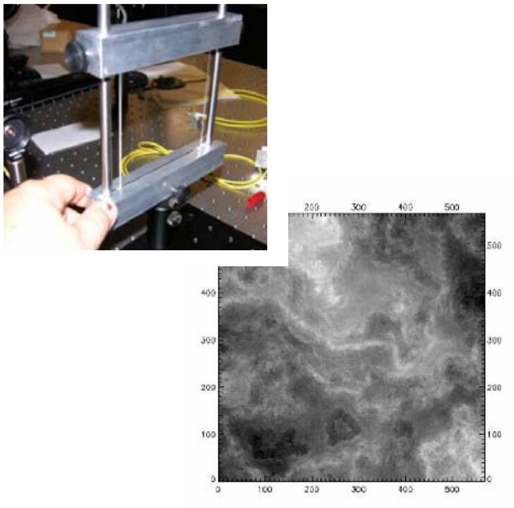

Figure 10b. Photo of the glass plate and measurement of a portion of the plate by the Quadrature Polarization Interferometer. The QPI clearly sees the terraces on the plate resulting from the step-etch process.

Hartmann wavefront sensors. The MCAO/MOAO testbed will use several Hartmann wavefront sensors. Astronomy graduate student Mark Ammons has been aligning and calibrating these sensors and has done considerable analysis to determine their ultimate measurement accuracy and precision. So far, we have achieved approximately 5 nm of accuracy and a fraction of a nm in precision/repeatability. This has been repeated for sensors on both the MCAO and the ExAO testbeds which differ in spatial resolution across the pupil but are otherwise identical.

Pyramid lenslet wavefront sensor. LAO consultant Brian Bauman (LLNL), in his PhD thesis, proposed a more light efficient alternative to the Hartmann wavefront sensor called the pyramid lenslet sensor[4]. It is a modification of a concept based on the traditional knife-edge optics test. A micro-optic array of lenslets splits the light at the focal plane into four quadrants which are each detected at subsequent pupil images. The bright and dark pattern in each of the four pupil images is processed to determine the wavefront. The pyramid configuration enables a much more sensitive (i.e. photon efficient) measurement of the wavefront under certain conditions.

The requirements on a suitable micro-optic are more exacting than what is obtained in common commercially available lenslets. We worked with a micro optic manufacturer, Vitrum Technologies, to produce a lenslet array to our specifications and tested it in a wavefront sensor arrangement in our laboratory. Initial results are showing very close agreement between wave optics simulations of light scattering off of a perfect micro-optic and measurements of the light scattering obtained with the Vitrum array (Figure 11), showing that it indeed has the required tolerances for wavefront sensing. This experiment will be completed when we measure aberrated wavefronts and compare results to Hartmann measurements. Astronomy graduate student Jess Johnson is performing the experiments.

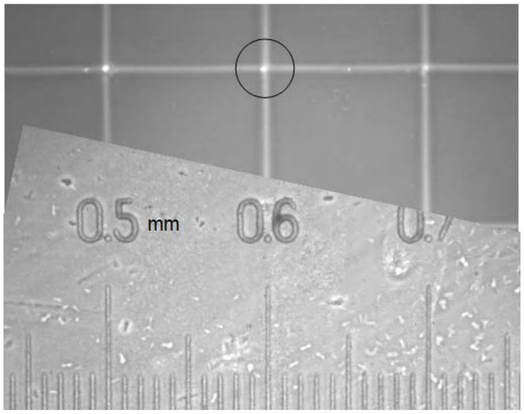

Figure 11a. Microscope photograph of the Vitrum lenslet array. These lenslets are 100 microns on a side and have edge imperfections that are smaller than a micron. The circle shows how a focused beam whose wavefront is to be measured would hit the array.

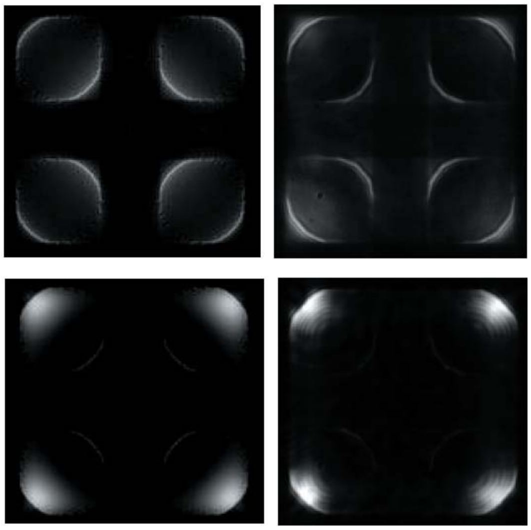

Figure 11b. Simulations [left] and measurements [right] of the pupil images after light passes through the pyramid lenslet. Pictures on the top row have no aberration. Pictures on the bottom row have defocus. A full wavefront phase map is recovered after simple processing of these pupil images.

Algorithm development. Major progress has been made on the tomography algorithms needed to command multiple deformable mirrors, given measurements from multiple laser guide stars. The initial work was done in collaboration with members of the Center for Adaptive Optics within its Adaptive Optics for Extremely Large Telescopes 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].

Donald Gavel and LAO computer engineer Marc Reinig, along with Electrical Engineering graduate student Carlos Cabrera, developed massively parallel architectures for the real time MCAO and MOAO control algorithms[6]. Mr. Cabrera, leading a group of four engineering students in a senior research project, programmed and tested a protoytype implementation of the tomography using a field-programmable gate array (FPGA). The results are very encouraging, proving that ELT (30 meter telescope) sized tomography, which in a traditional implementation would require the largest computer on the planet, can be implemented using today's FPGA technology with a modest number of chips. We were pleased when the senior project team led by Mr. Cabrera won the UC Santa Cruz best senior engineering project award as a result of this work.

Single conjugate AO testbed. A stand-alone single deformable mirror adaptive optics system was constructed last year by Astronomy graduate student Mark Ammons. This system uses a membrane type MEMS deformable mirror built by Intellite (now Agiloptic) Corporation. Mr. Ammons wrote the basic control software and user interface.

The single conjugate system has been used to develop system concepts that do not require using the entire MCAO testbed. For example, it has been used to test control algorithms and calibration procedures. It is also a useful learning tool for newcomers to the AO field. A second testbed (funded by the CfAO) was assembled by Mr. Ammons for use in a community college optics technician's course. The testbed has been used in hands-on demonstrations for laboratory visitors and students at the CfAO summer school.

Research Staff

Affiliated with the Laboratory for Adaptive Optics are Principal Investigator Claire Max, Co-investigators Joseph Miller and Jerry Nelson, and Laboratory Director Donald Gavel. Additional research staff who have been hired or who are doing substantial research work under fellowship or other support include:

Darren Dillon – Laser electro-optical mechanical engineer and laboratory manager.

Marc Reinig – Computers and electronics systems engineer.

Renate Kupke – Post doctoral researcher, PhD in Astronomy. Main experimentalist of MCAO/MOAO testbed.

Bruce Macintosh (1/2 time assignment from LLNL) – PhD Astronomer. Leader of the ExAO experiments and Principal Investigator for the ExAOC Gemini instrument.

Brian Bauman (1/2 time assignment from LLNL) – PhD Optical Engineer.

David Palmer (1/2 time assignment from LLNL) – Electrical and Computer Engineer. Project manager for the ExAOC Gemini instrument.

Lisa Poyneer (guest from LLNL) – Electrical Engineer. Performing ExAO wavefront sensing and control experiments.

Julia Evans (guest) – UC Davis Graduate Student in Applied Physics. Performing experiments characterizing MEMS and high contrast imaging on the ExAO testbed.

Scott Severson (guest from UCO/Lick) – PhD Research Astronomer. Helping with ExAO experiments.

Mark Ammons (on fellowship) – UCSC Graduate Student in Astronomy. Helping with MCAO/MOAO testbed.

Jess Johnson – Graduate student researcher, UCSC Graduate Student in Astronomy. Performing experiments with pyramid wavefront sensing and AO control on MCAO/MOAO testbed.

Katie Morzinski – Graduate student researcher, UCSC Graduate Student in Astronomy. Performing experiments characterizing MEMS on the ExAO testbed.

Carlos Cabrera – Graduate student researcher, UCSC Engineering Department. Designing, programming and testing massively parallel computer architectures for MCAO/MOAO tomography.

Summary

The Laboratory for Adaptive Optics is progressing very well 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 and have been selected to construct the Gemini Observatory ExAOC instrument. We have made substantial progress in establishing a testbed for a wide-field tomographic adaptive optics system for the next generation of extremely large telescopes, and we are actively testing key components for future AO systems. We have been able to hire outstanding staff, and we are well established in the permanent laboratory space of the LAO.

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Financial Report

[to be provided by Maureen McLean, UCO/Lick Business Office]