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

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Claire Max, Principal Investigator
Joseph Miller, co-Investigator
Jerry Nelson, co-Investigator
Donald Gavel, Laboratory Director

UCO/Lick Observatories
University of California
1156 High Street
Santa Cruz CA 95064

Executive Summary

The Laboratory for Adaptive Optics (LAO) has completed the fourth 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 can be achieved by space-based telescopes.

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

- The **Gemini Planet Imager (GPI) contract** was awarded and the project started in June, 2006. The Gemini Observatory selected the team led by Bruce Macintosh to build GPI, which is an extreme adaptive optics coronagraph designed to image and characterize planets outside our own solar system. Initial experiments at the LAO led to a successful proposal for this $22M instrument, marking a major milesone in accomplishing one of the main missions of the LAO. GPI is now being prototyped in the LAO, where we have just finished adding a coronagraph upgrade and demonstrated very high contrast imaging. GPI itself will be assembled and tested at the LAO during 2009 and 2010.

- We published the **first results from experiments on the Multi-Conjugate Adaptive Optics (MCAO) testbed**. These experiments demonstrated that correction with multiple guidestar tomography-based AO is superior to that from a single guidestar. Work is now proceeding using this reconfigurable testbed to demonstrate several proposed MCAO architectures for extremely large telescopes. Our team is collaborating with scientists from the Thirty Meter Telescope Project, Keck Observatory (Keck Next Generation Adaptive Optics), and Gemini Observatory.

- We have **begun planning for on-sky experiments of several AO technologies that have been developed in the laboratory.** The Visible Light Laser Guide Star (Villages) adaptive optics experiments will demonstrate, at the 40-inch telescope on Mt. Hamilton, the first use of MEMS deformable mirrors in an astronomical AO system. We also plan to demonstrate the first on-sky use of the spatially filtered Hartmann wavefront sensor and the pyramid-lenslet wavefront sensor, both of which were invented by LAO researchers.

- The LAO has **hosted a number of visitors and students from industry, academia, and summer programs** at UCSC. This year we have been developing a hands-on laboratory exercise for participants in the Center for Adaptive Optics Summer Schools. In 2005, Layra Reza from the CfAO mainland internship program joined us for the summer. Layra collected and analyzed data characterizing the performance of MEMS devices, using the interferometer in the ExAO laboratory.

The LAO is now staffed with one full-time research scientist, two full-time engineers, two postdoctoral researchers, and seven graduate students (representing Astronomy, Physics and Engineering across three UC Campuses), plus three half-time consulting scientists from Lawrence Livermore National Laboratory. Visiting scientist David LeMignant from Keck Observatory started a 1 year sabbatical at UCSC this month. David is the AO instrument scientist at Keck and will be actively involved in LAO experiments throughout Year Five.

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 was 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.

The Keck observatory has begun work on their Next Generation Adaptive Optics (NGAO) system. LAO Director Donald Gavel serves on its three-member executive committee (one representative from each of Keck, Palomar, and Lick Observatories) which is charged with planning and managing this project. The new Keck system will take advantage of many of the new technologies being developed at the LAO, and will in particular benefit from MEMS deformable mirror development and the MCAO and MOAO laboratory experiments.

The National Science Foundation's Adaptive Optics Development Program (AODP), administered by the National Optical Astronomy Observatory (NOAO) 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 have LAO participation in testing prototype components:

- Guidestar laser development (Dee Pennington at Lawrence Livermore)
- High-speed wavefront sensor detector development (Sean Adkins at Keck Observatory)
- Alternative design for high-speed low noise wavefront sensor (John Vallerga, UC Berkeley)

The Laboratory is clearly on the way to achieving its goals 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.

Fourth Year Status Report

Research Facilities

The LAO laboratory consists of two laboratory spaces totaling 1900 square feet in the Thimann laboratories building, located close to the UCO/Lick Observatory facilities, the UCSC Astronomy Department, and the Center for Adaptive Optics (CfAO) on the UC Santa Cruz campus. The facilities have environmental systems to control temperature, dust, lighting, humidity, and vibration to acceptable levels, which are crucial for the precise optical measurements performed there.

Laboratory facilities include

- A 200 square foot class 100 clean room which will enable ultra-clean assembly of the optical cells in the planet imaging instrument and provide an environment for tests where scattered light from dust particles must be kept to a minimum.
- Phase-shifting Diffraction Interferometer (PSDI) with the ability to measure absolute wavefronts to 0.1 nanometer accuracy.
- Quadrature Polarization Interferometer (QPI) for high speed interferometric measurements.
- Differential Imaging Contrast microscope for precise physical measurements and characterization of components (MEMS, spatial filters, Coronagraph stops, lenslets arrays)
- Adaptive Optics specialized electronics development area
- Separate optical tables for small research experiments
- Compute servers hosting a documentation/data library and the LAO website

In room 185, two large optical tables 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 1.

In room 191, an 18-foot long granite optical table accommodates the ExAO testbed with its point-diffraction interferometer and coronagraphic upgrade. The granite slab provides extra stability and vibration dampening in this ultra-precise experiment. The progression of layouts for this experiment is shown in Figure 2.

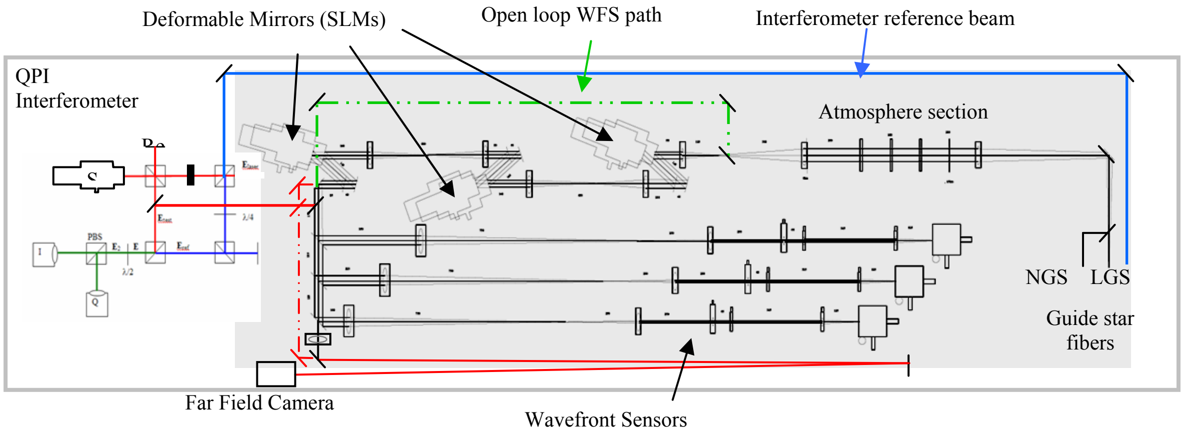


Figure 1. MCAO/MOAO Testbed showing major element and highlighting its reconfigurability for multiple guidestar wavefront sensors, closed loop (MCAO), and open loop (MOAO) architectures.

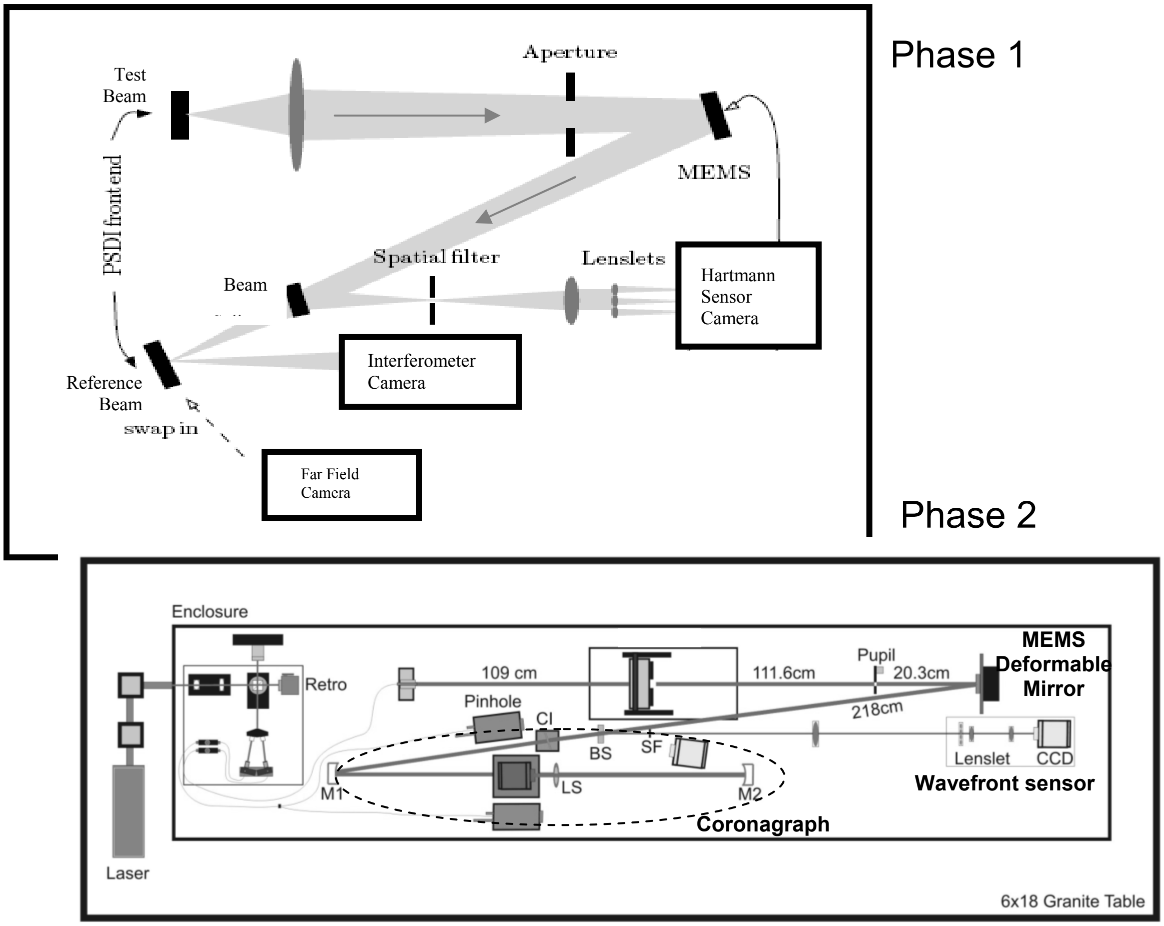


Figure 2. ExAO testbed progress from MEMS testing interferometer (Phase 1) to planet imager instrument prototype with diffraction-suppressing coronagraph (Phase 2).

Experiment Results: ExAO

The ExAO program, with the goal of direct imaging of 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 to date:

- The Phase-Shifting Diffraction Interferometer (PSDI) has proven the ability to measure wavefronts to less than 0.5 nm rms absolute accuracy over the long term.
- 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. This was tested and proven for the first time in the laboratory (Figure 3).
- The team led by LAO researcher Bruce Macintosh has been selected to build the Gemini Planet Imager (Extreme Adaptive Optics Coronagraph) for the Gemini Observatory. The contract for assembly, integration, and testing of this instrument has been awarded to the LAO. LAO scientist Bruce Macintosh is the Principal Investigator on this multi-institutional effort.
- The prototype extreme adaptive optics system has continued to make progress verifying concepts and establishing performance standards for the Gemini Planet Imager. We have recently added coronagraph optics for direct measurement of the far-field contrast simultaneous with closed loop AO control.

PSDI repeatability and stability

We have tested the long-term stability of PSDI looking at both a reference flat mirror and MEMS devices. A large part of our earlier 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 and long-term stable measurements of wavefront. Results of these tests were published in 2004 and 1005[2,3].

The coronagraph upgrade has added a number of elements into the optical path so we repeated the stability tests to assure that the resulting system was not degraded in accuracy. Tests are still in progress but early results indicate that the phase 2 system configuration is showing stability properties similar to the previous setup.

MEMS device characterization

We have completed our two-year development contract with Boston Micromachines Corporation to provide 1000-element MEMS deformable mirrors. They provided us with a total of 10 prototype 32x32 mirrors having various actuator designs. During our testing over this period we exchanged laboratory test information with BMC so that they were able to improve actuator yield and surface quality.

On a good device almost all 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 and BMC has worked with us to determine and mitigate the problems. 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. Results of this work were published in 2006[4].

Wavefront control experiments

Over the course of this development, increasingly complex MEMS wavefront control experiments have been performed to establish the capability of the system as a whole to achieve the high-contrast imaging required for ExAO. The steps involved are:

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.
4) With a coronagraph, measure the far-field corrected image to determine contrast possible with the flattened MEMS
5) With a coronagraph, measure the far-field corrected image after correction of an atmospheric aberration by the MEMS.

So far, we are approaching but have not yet achieved the goal for ExAO: a 1 nm rms total wavefront error after correction of turbulence. Ongoing experiments are continuing to uncover additional sources of small error[5,6].

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 [7], and was tested for the first time on the ExAO testbed. The results (Figure 3) show evidence of preserving the darkness of the discovery region[8].

Coronagraph contrast measurements

Last year we reported how, using a specially shaped pupil mask designed to suppress diffraction, we could control the MEMS to produce a far field image with a dark discovery region with better than 10^{-7} contrast. With the addition of the coronagraph upgrade we are now more clearly able to demonstrate a cleared-out discovery region (Figure 4). Initial tests are verifying that the wavefront quality and stability have been maintained in the coronagraph optics. One of the important goals of this effort is to evaluate selected optics manufacturers in their capability to polish the coronagraph's powered optics to precise mid-frequency figure specifications that are crucial to the success of GPI. These preliminary results are very promising.

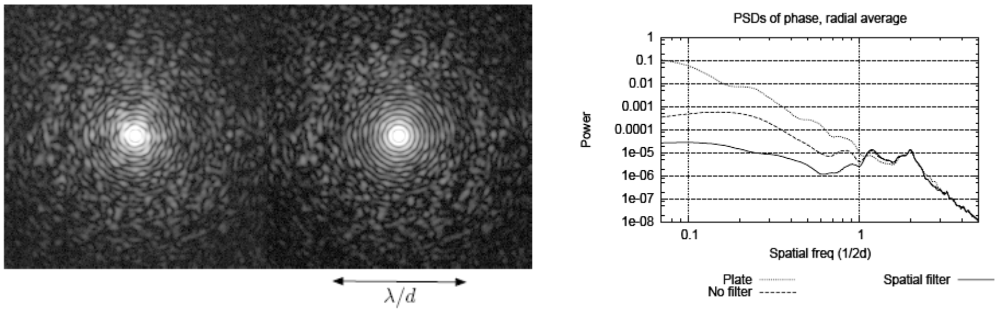


Figure 3. ExAO far-field image results with and without the Poyneer/Macintosh spatial filter modification to the Hartmann sensor. Closed loop correction of the phase aberration from a test aberrator plate is shown without [left] and with [right] the spatial filter. The improvement in correction which occurs in the λ/d central area manifests as much darker nulls between the Airy diffraction rings. The graph on the right shows quantitatively how flux energy is reduced in the controlled region.

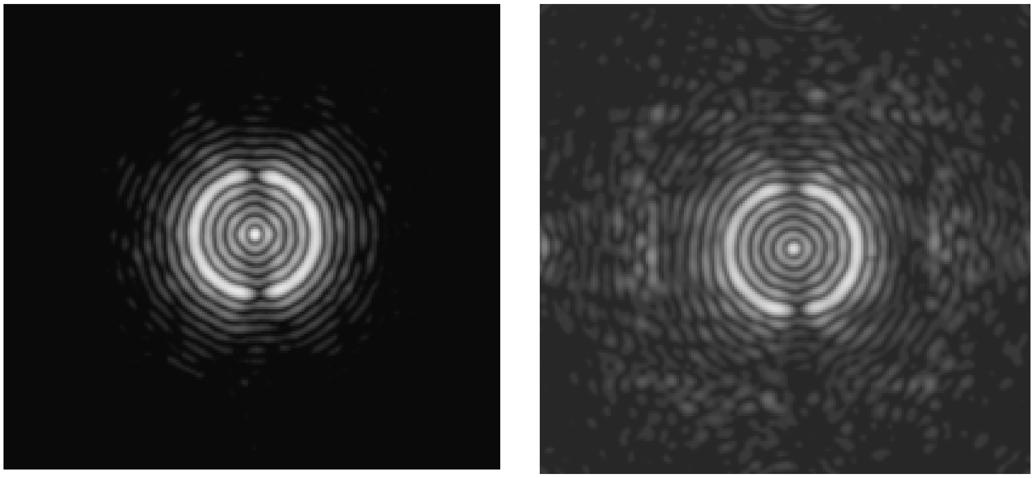


Figure 4. Early test results from the coronagraph upgrade showing far-field images, using a flat mirror in place of the MEMS mirror (left) and using a flattened MEMS (right). The diffraction rings in this image are considerably suppressed owing to the coronagraph, leaving the discovery region dark enough to image a planet. The grey-scale stretch of this image is 10,000 times higher than that of Figure 3; the residual scattered light outside of the 5'th ring from the center (the diameter of the coronagraph stop) is falling between 10^{-5} and 10^{-6} of the peak of the light which is blocked by the stop. We will also be testing an apodizing coronagraph stop that should further suppress the diffraction.

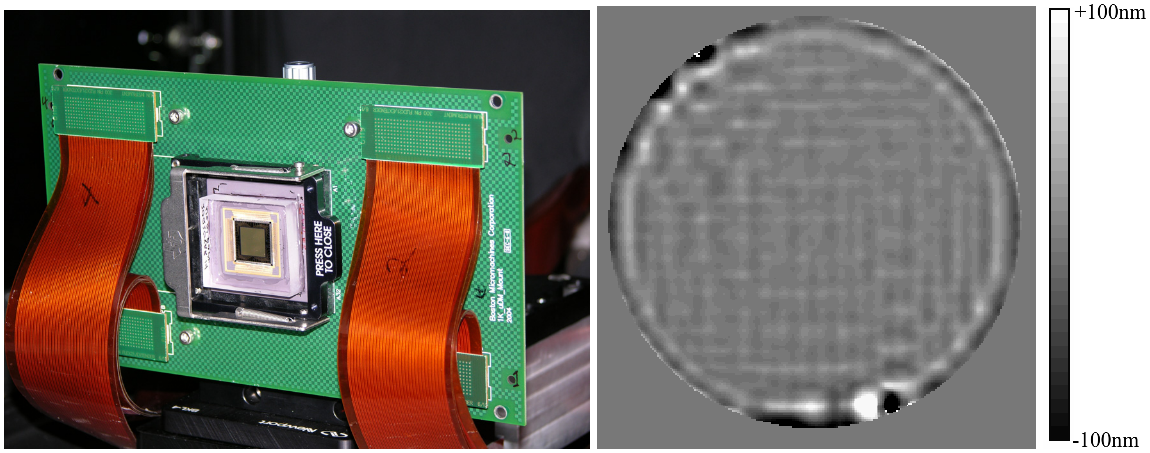


Figure 5. Left: the MEMS deformable mirror is shown in its mount. Right: grey-scale display of wavefront phase, as measured by PSDI, of a 9-mm diameter circular beam of light reflected off the central area of the MEMS. The MEMS device has a 10-mm square active area. An iterative algorithm using PSDI 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.

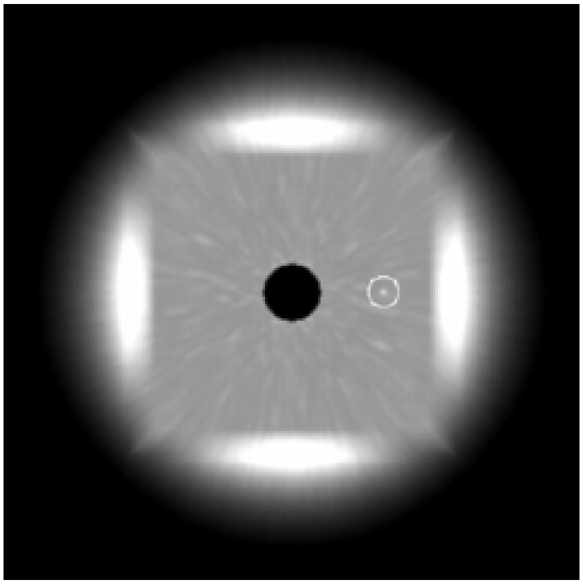


Figure 6. Simulation of the ExAO planet image using the GPI Coronagraph instrument. Wavefront control by the deformable mirror carves out a dark square planet discovery region around the central star. Light from the central star is blocked by an apodizing Lyot coronagraph which also suppresses diffraction. The image is multi-wavelength so the small remaining diffraction patterns blur out into a uniform background leaving only streaked speckles due to imperfections in the optics and wavefront sensor calibration, as allowed in the GPI instrument error budget. 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.

Experiment Results: MCAO

Multi-conjugate adaptive optics (MCAO), or more broadly, multiple-laser guidestar tomography for AO-corrected imaging, will enable wide-field diffraction-limited imaging for the "Extremely large" (>30-meter class) telescopes of the future. The test bench has completed an initial set of system characterization experiments and has demonstrated with a three guidestar constellation higher Strehl AO correction of over the field than is obtained using only one guidestar[9].

We are also pursuing innovative adaptive optics system concepts in the areas of wavefront sensing and MEMS open loop wavefront control in separate experiments.

MCAO experiments. 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

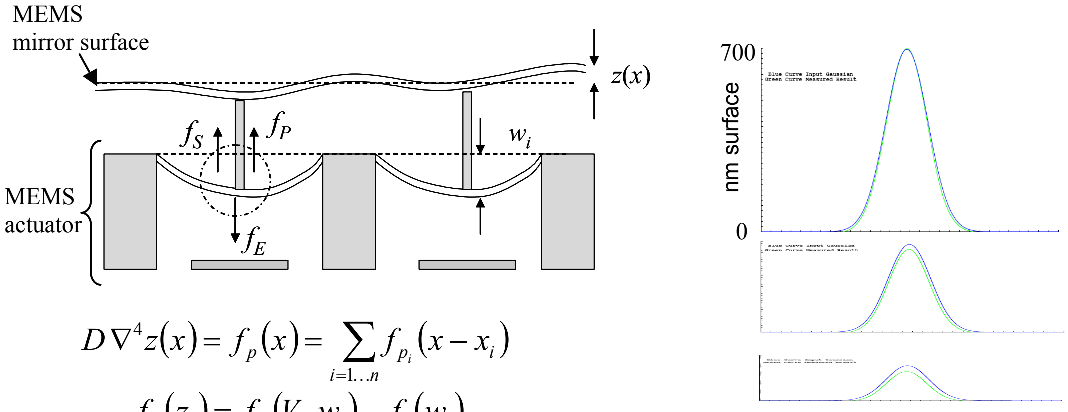
The MCAO optical testbed layout is shown in Figure 1. Light enters the system via laser fibers which emulate the guide stars, labeled NGS (natural guide star) and LGS (laser guide star) at the lower right of the figure. Here there is an array of sources to simulate a multi-guidestar constellation, plus 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. This interferometer records interferograms at high speed. The MCAO control system is designed to run at a quick pace (5 Hz, about a factor of 200 slower that a real-time AO control system on a telescope) while the phase aberrator plates are moved to simulate wind blown turbulence. This allows us to characterize the dynamic stability and performance 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 1). 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.

Component characterization. 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 to respond accurately to commands without having to be re-measured. In experiments on a second MEMS test station in the MCAO lab, we have been developing an open loop deformable response model based on the basic principles governing thin plates and electrostatic actuators. This model is used to predict the actuator voltages necessary to move the mirror surface to a precise given wavefront shape. Our tests are showing very promising results with one-step go-to correction achieving better than 30 nanometers peak-to-valley wavefront accuracy on the 32x32 MEMS devices[10]. This is actually adequate for the Thirty Meter Telescope’s MOAO instrument error budget goals but further development is ongoing to fully understand and improve upon this model for other applications.



$$D\nabla^4 z(x) = f_p(x) = \sum_{i=1\ldots n} f_{p_i}(x - x_i)$$

$$f_p(z_i) = f_E(V_i, w_i) - f_s(w_i)$$

Figure 7 MEMS open loop modeling. Left: The mirror response is modeled as a combination of thin plate force, electrostatic force, and spring return force of the actuator. A series of tests assuming the thin plate equation governs the relation between plate deflection and plate forces can be used to resolve each of the three force components separately. These are stored in a lookup table and used to drive the mirror to prespecified shapes in open loop. Right: Laboratory test results with the 32x32 Boston Micromachines MEMS showing the difference between modeled and actual surface shape is within 15 nm peak-to-valley (30 nm wavefront).

Some of the 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.

Hartmann wavefront sensors. The MCAO/MOAO testbed uses 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. Subsequent to the three-guidestar tomography demonstration we have modified the wavefront sensors to allow multiple guidestars per camera. This will allow up to eight guidestars total on 2 cameras with the third camera dedicated to tip/tilt star sensing, producing a full complexity mockup of the laser guidestar system that is envisioned for TMT instruments. The wavefront sensor optics and resulting Hartmann patterns are shown in Figure 8.

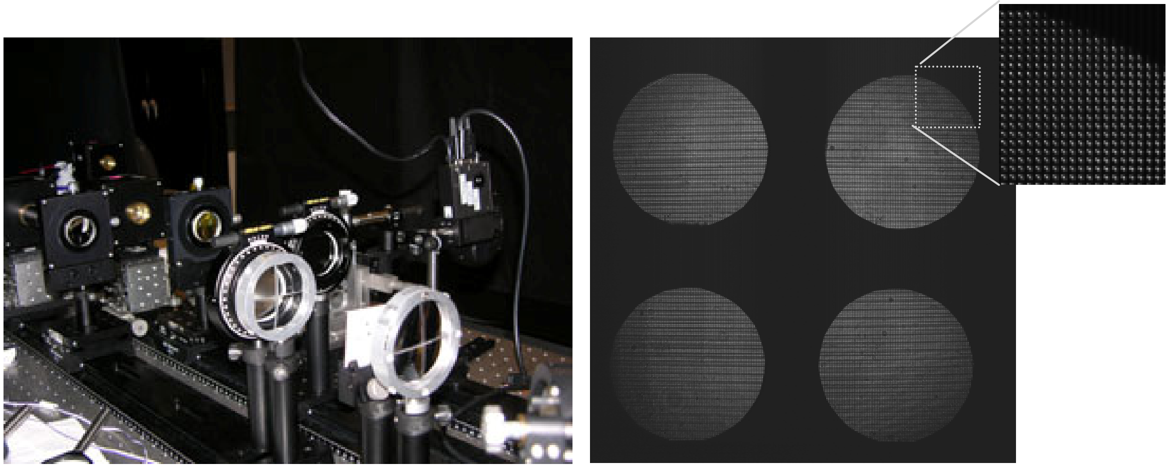
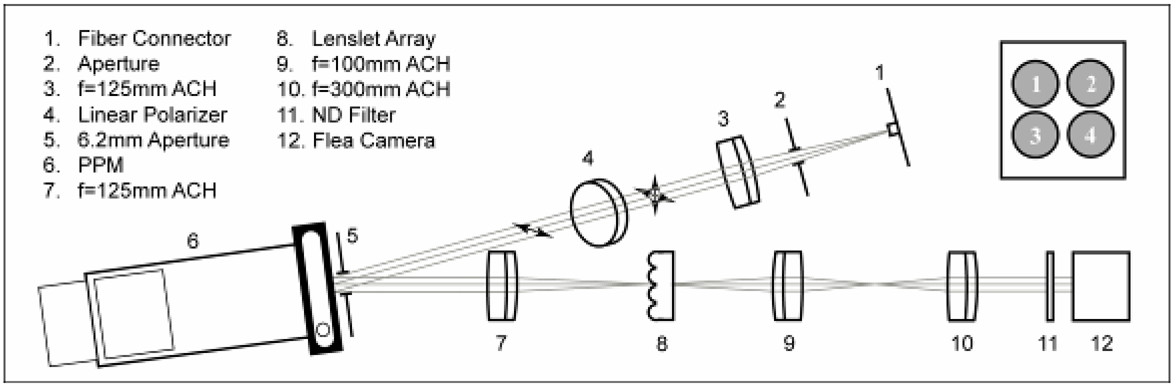


Figure 8. Left: photo of the multiplex wavefront sensor optics. Right, Hartmann patterns from multiple guidestars. The patterns have approximately 100 Hartmann spots across the aperture, protyping the TMT 10,000 degree of freedom AO system.

Pyramid lenslet wavefront sensor. LAO consultant Brian Bauman (LLNL), in his PhD thesis, proposed a light efficient alternative to the Hartmann wavefront sensor called the pyramid lenslet sensor[11]. 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. We have now completed measurements of the system performance with test aberration wavefronts generated by one of the spatial light modulators (Figure 9). Astronomy graduate student Jess Johnson is performing the experiments and initial results were reported at a recent adaptive optics conference [12].



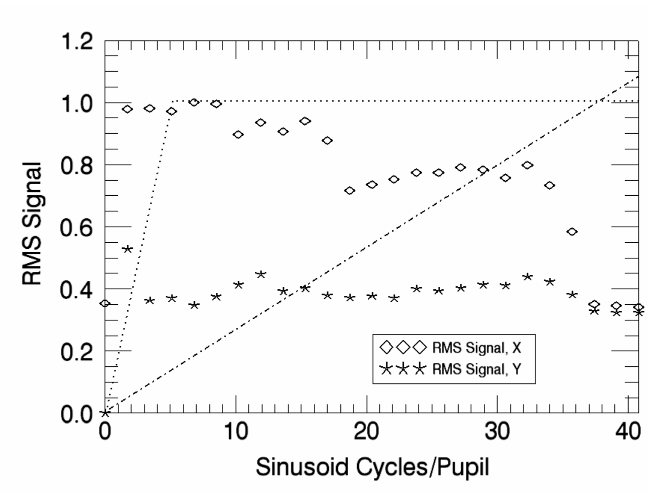


Figure 9. Pyramid lenslet wavefront sensor and experimental results. The response to phase aberration spatial frequencies is shown at the left, which is the first laboratory verification that the sensor acts to directly sense wavefront phase (uniform frequency response) as opposed to wavefront slope (linearly increasing with frequency). Furthermore the tests show the Nyquist cut-off (here at about 36 cycles/pupil) and an amplitude dependent nonlinearity of the sensor at 18 cycles/pupil, ascribed to second order diffraction.

Algorithm development. 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[13].

Gavel and LAO computer engineer Marc Reinig, along with Electrical Engineering graduate student Carlos Cabrera, have developed massively parallel architectures for the real time MCAO and MOAO control algorithms[14]. Mr. Cabrera programmed and tested a prototype implementation of the tomography reconstructor using a field-programmable gate array (FPGA) logic development kit. 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.

Plans are by the end of this year to test the massively parallel prototype system in closed loop on the MCAO testbed. The FPGA unit will be substituted in place of our traditional architecture (4 CPU) control computer and will be able to run a low resolution tomographic reconstruction and MCAO control (in the massively parallel world, higher order is achieved simply by adding more processors). Test results will be compared against identical runs using our standard computer.

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 2006 CfAO summer school.

MEMS AO / Visible Light Laser Guidestar (Villages) Experiments

MEMS technology and the two wavefront sensor designs developed at LAO, the spatially filtered Hartmann wavefront sensor and the pyramid lenslet wavefront sensor, are now mature enough to be tested on the sky under astronomical observing conditions. Since these technologies are new and have never before been used in astronomical instruments, a successful demonstration at a small telescope is beneficial, giving them a level of credibility needed to impact the design of future AO instruments.

We have completed a preliminary design of an AO system that will be mounted on the Nickel 40-inch telescope at Mount Hamilton. It will demonstrate, by the end of next year, MEMS based adaptive optics correction at visible to short infrared wavelengths (0.5 to 1.0 microns) in both the closed and open loop control configurations. This will in effect demonstrate the fundamental components and methods needed for an MOAO system on a large telescope.

The system will make diffraction-limited images at visible wavelengths using bright natural stars as reference beacons and will clearly demonstrate two key points to the astronomical community:

1) The feasibility of MEMS deformable mirrors as wavefront correctors in an astronomical adaptive optics system.
2) The unique capability of MEMS deformable mirrors to work accurately under open loop control with real starlight and in typical atmospheric turbulence conditions.

The configuration of the experimental instrument is shown in Figure 10. The system will be mounted at the Cassegrain focus (behind the primary mirror) of the Nickel 40-inch telescope. Light coming from the telescope on its way to the science camera reflects off of the MEMS deformable mirror, which applies the wavefront correction. The system is configured with two paths for starlight to enter into a Hartmann wavefront sensor of a multiplex design similar to those on the MCAO testbed. One path probes the wavefront prior to correction and other one after correction by the deformable mirror. This architecture enables either the closed or open loop operation and in each case provides diagnostic information about system performance by measuring both pre and post correction wavefronts simultaneously.

The system design for Phase 1 experiments has recently passed Preliminary Design Review, with reviewers representing the TMT Project, and the Keck, Palomar, and Lick Observatories attending. This review provided us with a valuable critique of the program plan and also guidance on our experimentation plans in view of their potential impact on future strategies for large telescope AO instrumentation.

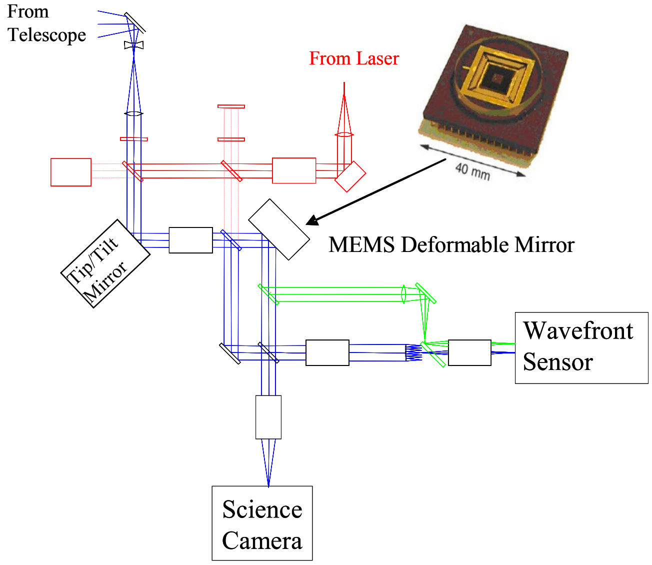


Figure 10. MEMS-AO / ViLLaGEs system. The system employs a 140 actuator MEMS deformable mirror and fits on the back of the Lick Observatory 40-inch Nickel telescope.

A proposal to the NSF Small Grants for Exploratory Researh (SGER) program has been submitted through the NSF Astronomy division to help defray costs of the experiment, with leveraged support coming from the Lick Observatory and LAO staffs.

A second phase of this project will involve projecting a sodium guidestar laser off the primary aperture of the 1-meter telescope (red lines in the figure). An adaptive optcis pre-correction of the beam for atmospheric aberrations the laser will encounter on the way up will produce an extremely small beacon, approximately 10 times smaller in angular extent than current LGS spots. Basic signal to noise calculations for wavefront sensing indicate that a factor of 10 improvement in beacon size will decrease the laser flux return requirements by a factor of 100. This would have a dramatic effect on the requirements for guidestar lasers, significantly reducing their cost and risk, and could possibly open the door to practical visible light laser guidestar systems.

We plan to pursue this second phase (first light ca. 2008) in collaboration with two AODP funded programs in solid state sodium laser development. Both of these programs (Dee Pennington at Lawrence Livermore and Ian McKinnie at Lockheed Martin Coherent Technologies) expect to have 5 to 10 Watt solid state lasers ready in this time frame.

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. Experimentalist on the MCAO/MOAO testbed.

Sandrine Thomas – Post doctoral reasearcher, PhD in Astronomy and Masters degree in laser technology. Experimentalist and analytic modeler for MCAO and ExAO.

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

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

Julia Evans (guest, 1/4 time consultant) – UC Davis Graduate Student in Applied Physics, recently graduated and transitioning to postdoctoral researcher at LLNL. 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.

Bautista Fernandez – Graduate student researcher, UCSC Engineering Department, Designing and testing MEMS.

Eddie Laag – Graduate student researcher, UC Riverside Astronomy Department. Performing experiments on the MCAO testbed.

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 contracted to construct the Gemini Planet Imager 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, we are actively testing key components for future AO systems, and we are proceeding to on-sky experiments of the technology developed in the lab. We have a world-class adaptive optics research staff and are publishing results at a high rate.

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