**Laboratory for Adaptive Optics**
*UCO/Lick Observatory*
*University of California, Santa Cruz*

# Seventh Year Status Report for
# The Laboratory for Adaptive Optics
# UC Santa Cruz

Submitted to the
Gordon and Betty Moore Foundation

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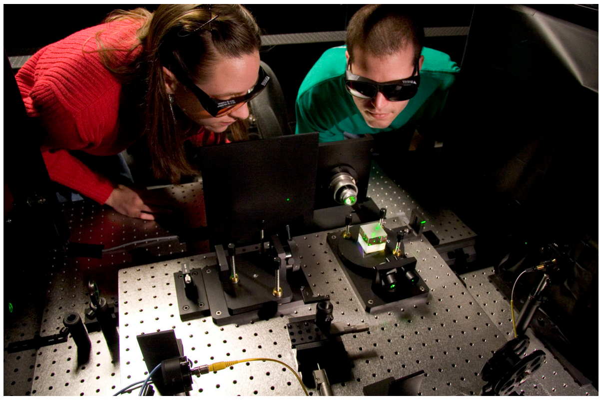
## Executive Summary

The Laboratory for Adaptive Optics (LAO) has completed its seventh and final year under the founding grant from the Gordon and Betty Moore Foundation, having established a permanent development laboratory affiliated with the University of California Observatories (UCO) and accomplishing several important milestones in the development of next generation adaptive optics technology. Since its formulation in August 2002, the Laboratory has been a key contributor to new astronomical adaptive optics programs for the Keck Observatory, for the Gemini Observatory, and for the Thirty Meter Telescope Project. We fielded an experimental AO system on Mount Hamilton that has been used to demonstrate MEMS deformable mirror technology and will later next year test a new fiber laser technology for generating artificial guidestars that are crucial for using AO over the entire sky. Recently, the Astronomy Division of the National Science Foundation awarded a three-year Major Research Instrumentation grant to the LAO team to build a MEMS mirror based AO system for the Shane 3-meter telescope on Mount Hamilton. This system will demonstrate many of the concepts developed in the lab, will greatly extend the Lick Observatory science capabilities and will be a crucial pathfinder and field demonstration of the components and algorithms planned for the next generation AO systems on 8-meter diameter and larger telescopes around the world.


Graduate students Katie Morzinski and Mark Ammons examine the laser front-end module of the PSDI interferometer in the Laboratory for Adaptive Optics.

The charter goals of the LAO are to develop adaptive optics technology, concepts, and instruments for astronomy. These goals have been accomplished with three main facilities: a Multiconjugate Adaptive Optics (MCAO) Laboratory; an Extreme Adaptive Optics (ExAO) Laboratory, and a Component Testing Laboratory. All are aimed at improving the ability of ground-based astronomical telescopes to correct for blurring due to the Earth's atmosphere. With such systems, telescopes on the ground can make diffraction-limited images as sharp as those of space-based telescopes.

**At the Laboratory for Adaptive Optics, we have pursued a number of very forward-looking, high-risk, high-return programs that otherwise would not have been possible. This was accomplished because of the independent nature of the funding in the Moore Foundation grant and is consistent with the Moore Foundation's goal of advancing forefront scientific research and technology.** The results described in the following pages give a very gratifying vindication of how well this approach is paying off.

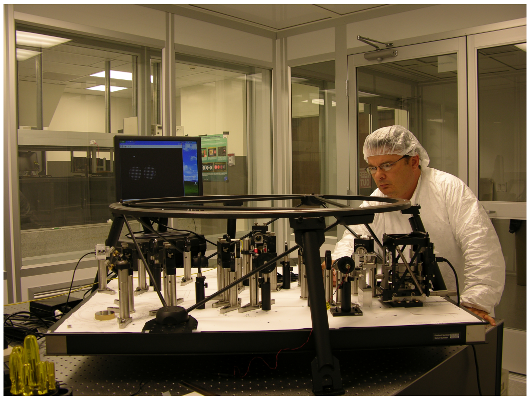
We have achieved the following milestones**:**

- **The LAO plays a key role in the preliminary design of the Keck Next Generation Adaptive Optics (NGAO) system**. This system is a multiple-laser guidestar AO system that utilizes tomography to measure and correct for the volume of turbulent atmosphere above the telescope. The method is analogous to medical CAT scans: both obtain information from many different angular views and use the data to reconstruct three-dimensional information. We are working with researchers from the Keck Observatory and Caltech Optical

Observatories in the design the system and in performing key risk-reduction experiments in our laboratory to bolster the technology case for the feasibility of multi-laser guidestar AO. A number of research papers based on LAO experimental results have been published and LAO graduate student, Mark Ammons, has completed his PhD degree. Ammons focused the instrumentation component of his thesis around LAO tomography experiments. The Keck NGAO system will enable a wide variety of new high-resolution science observations in the following fields: asteroids and minor planets in our own Solar System, star and planet formation in the solar neighborhood, activity around the black hole at the center of our Galaxy, and the formation and evolution of galaxies in the early universe. PI Claire Max is the Keck NGAO project scientist, and Laboratory Director Donald Gavel is the UC representative on the project's senior management team.

- The **Gemini Planet Imager (GPI) project.** In 2005, the Gemini Observatory selected the team led by LAO researcher Bruce Macintosh to build GPI, designed to image and characterize planets outside our own solar system, for the Gemini Observatory. GPI uses high-order adaptive optics with a MEMS mirror and a specialized coronagraph to suppress atmospheric aberrations and diffracted light from the parent star, to image orbiting planets that are more than seven orders of magnitude dimmer. GPI has now nearly completed its build phase. Assembly, integration, and test will take place in the Lick Observatory shops (on the UCSC campus) under the direction of LAO staff during late 2009 and 2010. First light at the Gemini South observatory is scheduled for early 2011. Prototype experiments in the LAO ExAO testbed enabled the development of the technology and the successful proposal for this $22M instrument, furthering one of the main missions of the LAO. Graduate student Julia Evans received her PhD degree from UC Davis based upon her LAO work in this area. In collaboration with visiting researchers, our ongoing experiments this year have made major progress in developing deep-contrast wavefront control techniques that further enhance the planet signal above background noise.

- **The Villages adaptive optics system has been built mounted on the Nickel Telescope at Lick Observatory and it is producing diffraction-limited images at visible wavelengths.** This system is the observatory-based proving ground for LAO developed technologies. It has successfully demonstrated the MEMS technology for on-the-telescope use and is being prepared for incorporation of a new guidestar laser in the coming year.


Lab Engineer Daren Dillon assembles the Villages adaptive optics system in the LAO cleanroom facility.

- **The LAO continues to be a training ground for graduate students and postdocs in Astronomy, Physics, and Engineering.** Our first astronomy student was recently graduated with a PhD. Two more astronomy students and one engineering student presently working in the lab have passed their PhD qualifying exams. Four additional engineering students and one physics student are also conducting research in the LAO. The LAO has hosted a number of visiting researchers and students from other UC campuses, and from both Caltech and JPL. Each year, the Center for Adaptive Optics (an NSF-sponsored science and technology center) has a week-long adaptive optics summer school at UCSC. The LAO hosts the laboratory components of the school; PI Max and Director Gavel taught key classes. The LAO core research staff includes two full-time research scientists, two full-time engineers, and one associate specialist. Eight graduate students (representing Astronomy, Physics, Earth Sciences and Engineering), and three half-time consulting scientists from Lawrence Livermore National Laboratory are also employed.

Graduate student researcher Katie Morzinski gives a tour of the LAO to prospective UCSC astronomy graduate students.

- **The National Science Foundation has awarded a grant to the LAO team to design and build a MEMS based AO system for the Lick Observatory Shane telescope.** This 3-year $2M grant is from the Major Research Instrumentation program, which is intended for modernizing research facilities at academic institutions. This new AO system will use the technologies developed at the LAO to enhance the infrared science target sensitivity and increase the wavelength coverage for adaptive optics at the Shane 3-meter telescope.

The broader AO and astronomy communities have shown its keen interest in LAO developments. In December 2003 the Gordon and Betty Moore Foundation granted $17.5M to the University of California to help fund the conceptual design for a 30-meter telescope. LAO co-Investigator Professor Jerry Nelson is the Project Scientist for the 30-meter telescope project, and LAO Director Dr. Donald Gavel served as chairman of the initial Adaptive Optics Working Group. We continue regular interaction with the TMT adaptive optics project team and have defined a number of testbed experiments and component development efforts based on our discussions with them. TMT Project Manager Gary Sanders and AO Manager Brent Ellerbroek are enthusiastic supporters of the efforts and regularly monitor our progress. Brent Ellerbroek served on the design review committees for the Keck NGAO and Villages projects.

The National Science Foundation's Adaptive Optics Development Program (AODP), administered by the National Optical Astronomy Observatory (NOAO) supported 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 had LAO participation:

- Guidestar laser development (Jay Dawson 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 National Aeronautics and Space Administration (NASA) has several pilot projects in developing high-contrast AO systems and coronagraphs for space-based telescopes with exo-planet observing missions. LAO has collaborated with NASA Ames Research Center to develop and characterize MEMS devices for advanced coronagraph wavefront control.

**In summary**: the Laboratory for Adaptive Optics has achieved its charter goals of providing a venue that serves the 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.

# Seventh Year Status Report

## Research Facilities Status

The research facilities of the Laboratory for Adaptive Optics consist of three large laboratory spaces and 846 square feet of offices in the Thimann Laboratories Building. The location is on Science Hill close to the UC Observatory Headquarters, the UCSC Astronomy Department, and the Center for Adaptive Optics (CfAO) on the UC Santa Cruz campus. The Laboratory has the latest environmental systems to control temperature, dust, lighting, humidity, and vibration to acceptable levels for optics laboratory requirements, including 414 square feet of class 100 clean room area.

Laboratory facilities include

- A class 100 clean room which enables ultra-clean assembly of the optical cells in the planet imaging instrument and provides 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, lenslet arrays, etc.)
- Interferometric microscope with high speed sample strobe capability. This microscope is designed for measuring long-stroke motion of MEMS actuators to very high accuracy (<1 nm) with microsecond time resolution.
- Specialized for Adaptive Optics electronics development area
- Separate optical tables for individual research experiments
- Compute servers hosting a documentation/data library and the LAO website

In Thimann Labs 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 Thimann Labs Room 191, an 18-foot long granite optical table accommodates the ExAO testbed for high-contrast imaging, with its phase- shifting diffraction interferometer (PSDI) and coronagraphic imaging capability. The granite slab provides extra stability and vibration dampening in this ultra-precise experiment. The progression of layouts from PSDI to PSDI+coronagraph is shown in Figure 2.

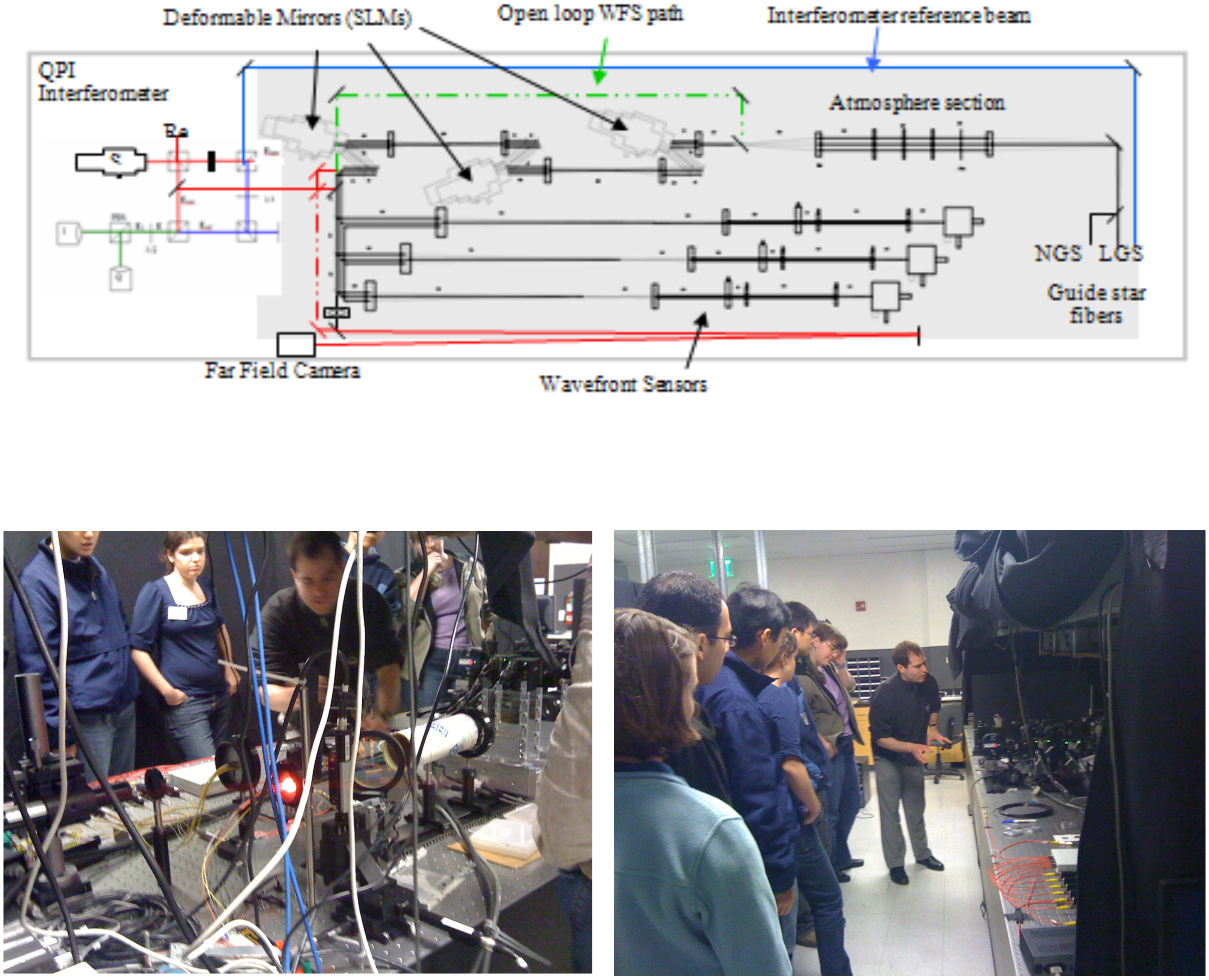


**Figure 1**. Top: Multi-guidestar adaptive optics testbed layout, showing major element and highlighting its reconfigurability for investigating different system architectures. Bottom: Graduate student researcher Mark Ammons demonstrates the testbed capabilities to a group of visiting astronomy students.

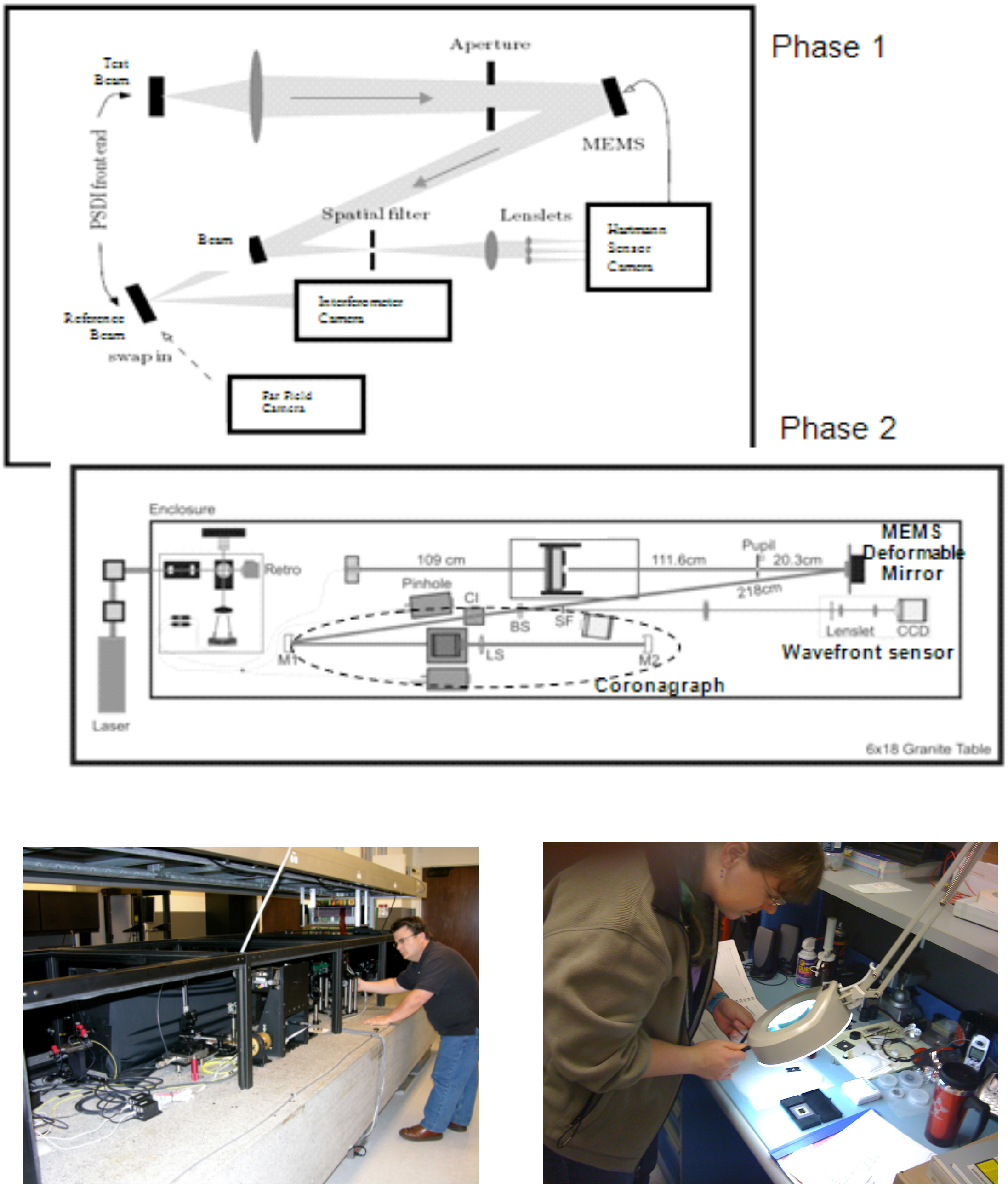


**Figure 2. Top**: ExAO testbed layouts, from MEMS testing interferometer (Phase 1) to planet imager instrument prototype with diffraction-suppressing coronagraph (Phase 2). **Bottom**: Left: lab engineer Daren Dillon adjusts the alignment of optics on the testbed. Right: a visitor views a MEMS device through a magnifier.

## Experiment Results: Extreme Adaptive Optics Testbed for Planet Imaging

The ExAO program, with the goal of direct imaging of extrasolar planets, takes 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[1,2]. Careful control of the wavefront will provide the high contrast to separate the light from the planet from that of the much brighter parent star. The science requirement calls for a ground based instrument to detect a planet at a level $10^7$ times dimmer than the star. This is several orders of magnitude better than the presently fielded imagers can accomplish. To that end, the baseline is to control the wavefront to extreme accuracy using adaptive optics and to suppress scattered light from diffraction with a specially designed coronagraph. The LAO's ExAO testbed provides the prototype for both of these.

Here is a list of milestones accomplished to date using our ExAO testbed:

- 2004: The Phase-Shifting Diffraction Interferometer (PSDI) proved its capability to measure wavefronts to less than 0.5 nm rms absolute accuracy with long term stability and repeatability.
- 2004: A 32x32 actuator MEMS deformable mirror was controlled to a flatness of less than 1 nm rms and generated a high contrast ($<10^{-6}$) far-field image.
- 2005: MEMS deformable mirrors were controlled to "undo" the aberrations of a test aberrator plate down to less than 3 nm rms wavefront error.
- 2005: 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 proved the Hartmann sensor to agree with the PSDI to about the 2.2 nm level and characterized and quantified the remaining sources of systematic and random error.
- 2004-5: A new concept for precise Hartmann wavefront sensing without aliasing error was developed by Bruce Macintosh and Lisa Poyneer. This was published as a theoretical paper in 2004 and tested and proven for the first time in LAO experiments in 2005.
- 2005: The team led by LAO researcher Bruce Macintosh was 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.
- 2006-7: An apodized pupil Lyot coronagraph of the type to be used in GPI was designed, fabricated, installed, and tested in the Phase 2 arm of the ExAO testbed. Using the coronagraph and a 32x32 MEMS device we demonstrated $2\times10^{-7}$ contrast ratio over a field of view effective for planet imaging.
- 2008: The first 64x64 MEMS deformable mirror was delivered to LAO. This first device is "engineering grade" but demonstrated <1nm flattening over a 16 mm area of the mirror. The "science grade" device to be installed into GPI is due for delivery later in 2009.
- 2009: A portion of the engineering grade 64x64 MEMS device was controlled to produce a level of $4\times10^{-8}$ contrast in apodized pupil Lyot coronagraph tests.

## *MEMS Device Fabrication and Testing*

In 2005 we completed a two-year contract with Boston Micromachines Corporation (BMC) to develop 1024-element continuous mirror face-sheet MEMS deformable mirrors. BMC delivered a total of 10 prototype devices having a progression of actuator designs in a trade of actuator stroke, spatial response function of the face sheet, and surface roughness. During our testing over this period we provided laboratory test results to BMC which guided their manufacturing process in order to meet our exacting requirements[4].

We then initiated a contract with BMC to develop the first ever 4096 (64x64) element MEMS deformable mirror. The development portion was supported through a combination of LAO and CfAO funds, with the requirements on the MEMS device set by needs solicited from the astronomical science community with consideration of future 30-meter telescope and 10-meter telescope applications as well as to ExAO planet imaging[5]. Full scale fabrication of the science grade devices was funded by Gemini through the Gemini Planet Imager subaward. We now have received our first engineering grade 64x64 devices for testing (Figure 3). The final device will be selected so that at least a 48 actuator diameter area of the MEMS is free of defects (all actuators working and the surface reflectivity and smoothness meet specifications). In the engineering device about 2% of the actuators are not working, but there is a 33 actuator diameter area over which we can perform useful tests. This device has been successfully flattened in the ExAO testbed using the PSDI interferometer to less than 1 nm rms over this controlled area.

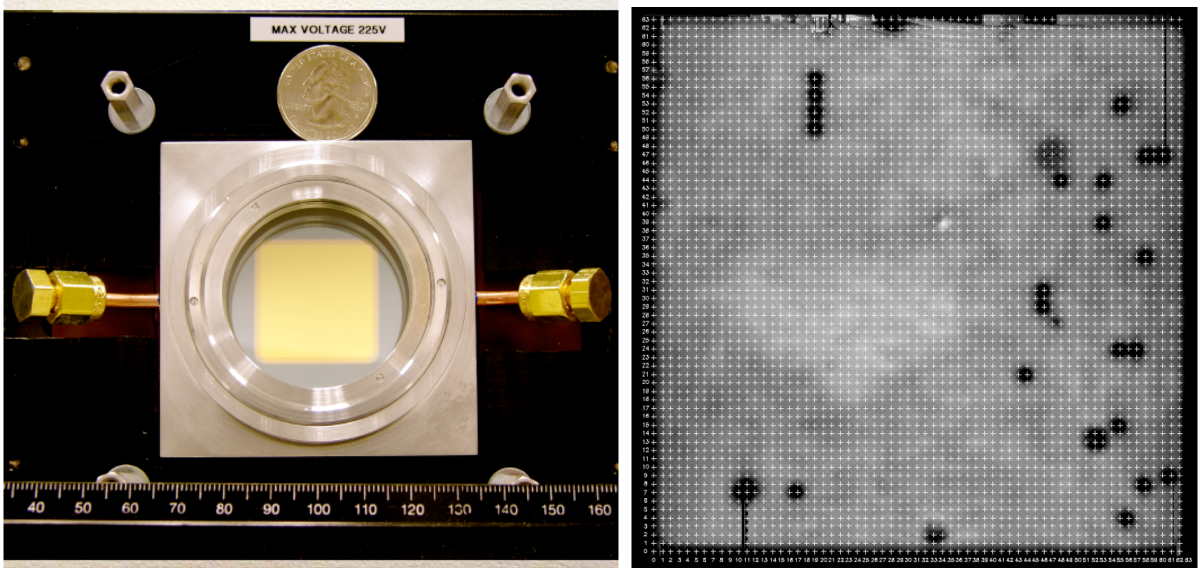


**Figure 3**. 4096-actuator engineering grade MEMS mirror recently delivered to LAO. Left: the device is shown in its protective chamber, with window and dry air ports. Right: a PSDI measurement of the flattened device, showing a number of dead actuators. A clear region of about 32 actuators across is available for further testing in the ExAO testbed. The contract requires delivery of a science grade device with 48 actuator diameter clear region.

### *Coronagraph Contrast Measurements*

Prior to the Phase 2 upgrade of the ExAO testbed to full coronagraphic capability, we performed experiments using a specially shaped pupil mask to help suppress diffraction over a limited wedge-shaped area in the focal plane. With this, we demonstrated better than $10^{-7}$ contrast in this narrow area[8-11]. With the addition of the coronagraph arm we are now able to demonstrate a dark discovery region that fully surrounds the star.

In 2007 we began receiving components for a custom apodized pupil Lyot coronagraph. These were designed from basic mathematical and wave-optic principles for maximum scattered light suppression by Princeton University collaborator (now with Space Telescope Science Center) Remi Soummer[12] (Figure 5). The pupil apodizer and focal plane stop work together to suppress diffraction rings within the planet discovery region that would otherwise be produced by the sharp edges of apertures and stops within the system. After several iterations with the manufacturing process (still ongoing) we achieved an acceptable set of matched apodizer elements and focal plane stops with which we can experiment. Testing in conjunction with the 32x32 MEMS deformable mirrors has demonstrated acceptable results that can be extrapolated to the GPI instrument.

The latest ExAO testbed results using the new 64x64 MEMS device are shown in Figures 5 and 6. Guest scientist Amir Givon from the Jet Propulsion Laboratory worked with LAO scientist Sandrine Thomas to test a new iterative calibration scheme for further reducing scattered light in the planet discovery region. The technique uses additional data from the focal plane image to make fine adjustments to the deformable mirror's commands to reducing total light in the discovery region. The results demonstrated that the calibration process can continue to increase contrast by approximately a factor of 5 from the starting point set by PSDI wavefront measurements.

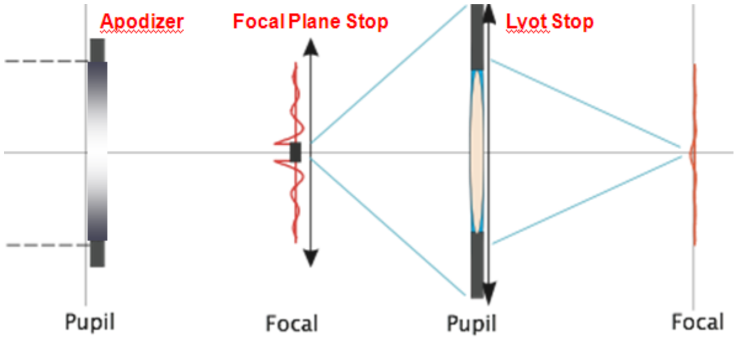


**Figure 4**. The apodized Lyot coronagraph optics concept. Three optical elements comprise the coronagraph. The first, a pupil apodizer, tailors the beam profile to minimize scattered light from the sharp edges of the telescope aperture. The second, a focal plane stop, blocks most of the light from the central star (the planet light goes around this stop. The Third, a Lyot stop, blocks residual star light that has been scattered by the focal plane stop, which is at this point concentrated around the edges of the pupil.

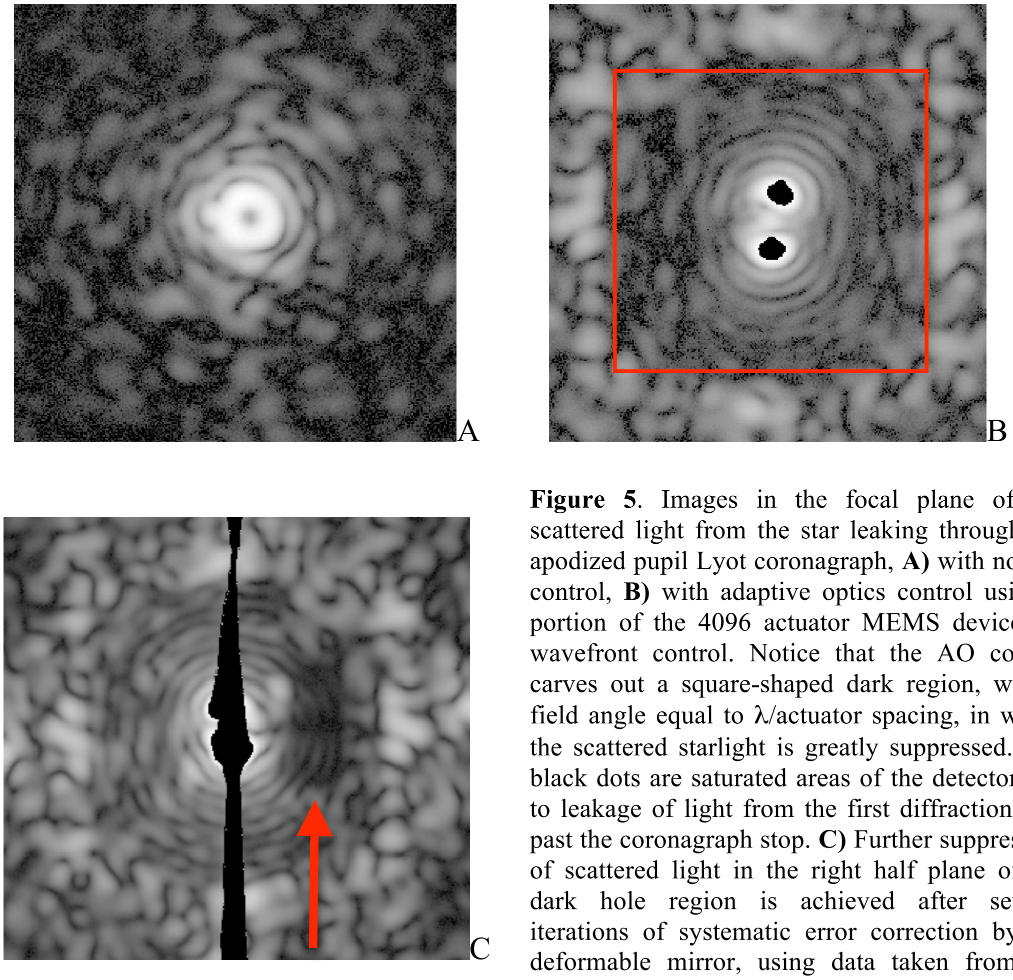


**Figure 5**. Images in the focal plane of the scattered light from the star leaking through the apodized pupil Lyot coronagraph, **A)** with no AO control, **B)** with adaptive optics control using a portion of the 4096 actuator MEMS device for wavefront control. Notice that the AO control carves out a square-shaped dark region, with a field angle equal to λ/actuator spacing, in which the scattered starlight is greatly suppressed. The black dots are saturated areas of the detector due to leakage of light from the first diffraction ring past the coronagraph stop. **C)** Further suppression of scattered light in the right half plane of the dark hole region is achieved after several iterations of systematic error correction by the deformable mirror, using data taken from the image plane. Such a calibration scheme improves the signal to noise ratio for imaging a planet in this region. (All images are displayed as log-intensity for clarity.)

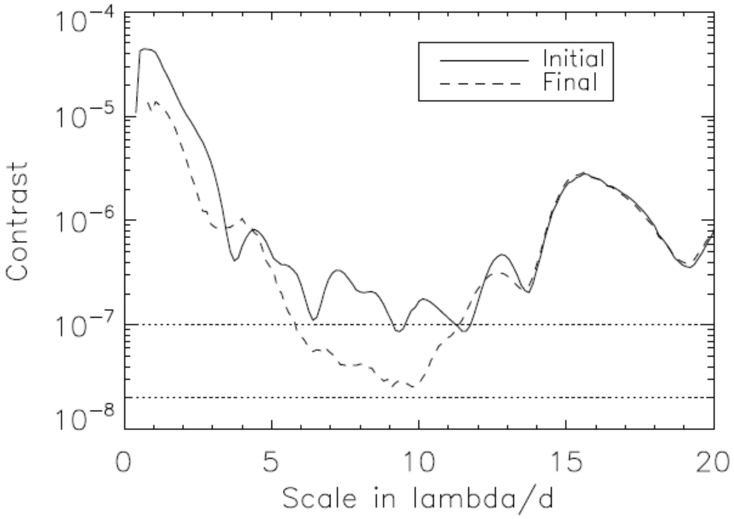


**Figure 6**. Radially averaged contrast versus field angle. The region between 3 and 6 λ/D (where D is the aperture diameter and λ is the observing wavelength) has the deepest suppression of scattered light. The solid curve is MEMS AO-corrected. The dashed curve is MEMS AO-corrected including several iterations of the systematic error correction. The image contrast is 4 x $10^{-8}$ in a section of the planet discovery region between 6 and 10 λ/D. This contrast readily meets the requirements for the GPI baseline design.

### *MEMS Stability and Hysteresis Measurements*

MEMS devices have an advantage over earlier deformable mirror technologies in that the actuation process is inherently accurate and precisely repeatable. We designed an experiment to measure the sub nanometer hysteretic (non-repeatable) behavior by repeatedly actuating to a given command point coming from different directions (hysteretic response depends on direction of approach)[3]. We found that the MEMS actuator actually exhibits both a fast and slow response component, but that no hysteresis is apparent at the ~0.5 nm level.

Future use of MEMS for even higher contrast extreme adaptive optics applications, such as might be deployed on a spacecraft platform for imaging earth-like planets around stars, will require even finer repeatable positioning accuracy. However spacecraft applications can tolerate the slower response since they are correcting internal aberrations and don't need to keep up with a rapidly changing atmosphere. In anticipation of this need, we are now constructing a second diffraction interferometer and coronagraph testbed that will be smaller, stiffer, and enclosed in a very precise temperature controlled environment. The goal is to reduce the systematic error in wavefront measurement by a factor of ten, which will make the system suitable for testing coronagraphs and ExAO control to the level of $10^{-9}$ contrast.

### *Intensity variation measurements*

In an extreme adaptive optics system, intensity variations matter as much as phase variations. Starlight provides very uniform illumination, even after propagation through the atmosphere, but intensity variations introduced by the instrument optics can be detrimental to final image contrast. In order to meet planet imaging specifications, the reflectivity variations on the MEMS surface must be less than a few percent. Furthermore, phase variations can be inadvertently converted to amplitude variations via Talbot imaging. Thus extreme care must be taken to minimize additional phase error at all optical surfaces of the instrument. We measured phase induced amplitude variations in the coronagraph configuration (ExAO testbed Phase 2) both with the MEMS device and with a flat mirror in its place and concluded that the MEMS does not add detectable amplitude errors above those expected from the coronagraph optics. Independent tests of MEMS reflectivity have also confirmed the upper bound of a few percent variation.[6,7,30]

## Experiment Results: Multi-Conjugate Adaptive Optics Testbed

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. This test bench is now producing important results through demonstrations of tomographic wavefront sensing and multi-conjugate wavefront control.

In addition, we are pursuing innovative adaptive optics system concepts in the areas of wavefront sensing and MEMS open loop wavefront control in separate experiments.

### *Tomography experiments*

To perform laboratory experiments relevant to 10 to 30 meter diameter telescopes, one must scale 60 km of turbulent atmosphere and the telescope aperture to fit on a room-size optical bench, while still retaining the proper diffractive behavior of the optical system. These scaling considerations have driven the optical design and layout of the testbed, with the net result that a variety of AO concepts for different telescopes can be configured in the lab.

The table below shows the testbed configurations for which we have published AO tomography results[13,14]. Earlier years' results have been highlighted in our prior status reports. The main thrust this year was to test tomography concepts for the 10 meter Keck telescope's Next Generation AO system, where there are demanding requirements for low residual wavefront error and a correction suitable for shorter wavelength bands than have been previously corrected by astronomical AO systems.

**Table 1**. Experiments performed on the multi-guidestar testbed

| Year | Modeled System | Modeled Telescope Diameter | Pupil sampling | Science Wavelength |
|---|---|---|---|---|
| 2006 | TMT NFIRAOS | 30 | 70 across | 2.5 microns |
| 2007 | Gemini MCAO | 8 | 36 | 2.2 microns |
| 2008 | Keck | 10 | 36 | 0.9 microns |
|  | Keck NGAO | 10 | 64 | 0.6 microns |

The testbed can be configured for both multi-conjugate AO correction (MCAO) and multi-object AO correction (MOAO). In the MCAO arrangement deformable mirrors are placed at locations along the optical path that are conjugate images of various altitudes in the atmosphere. The conjugate mirrors work together in series to provide moderate correction over a field of view suitable for a wide field imaging camera. Gemini's MCAO system is arranged in this manner and it is the baseline design for TMT NFIRAOS. The MOAO configuration has one deformable mirror per science direction, each one at an image of the primary mirror. The idea is to do an excellent correction on multiple selectable small fields, which is the ideal configuration for a multi-slit spectrometer or multiple unit integral field spectrograph. The later is the idea behind TMT IRMOS (Infrared Multiple Object Spectrograph) instrument and Keck NGAO.

*Optical path – Multi-Conjugate Adaptive Optics (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 a science object at arbitrary locations in the field. The guide star and science object light travel through a series of phase aberration plates in the atmosphere section, to emulate multiple layers of air turbulence at different altitudes in the Earth's 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 optical 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 while the phase aberrator plates are moved to simulate wind blown turbulence. With the laboratory system we are able to run at approximately 1/200 of the speed of what a real-time controller would operate; this is merely to save the considerable expense of a real-time controller (described in more detail below) but allows us still to run faster than numerical simulations and make useful conclusions about the long-term dynamic stability and performance of MCAO control algorithms.

*Optical path – Multi-Object Adaptive Optics (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 tomographic model of the entire volume of atmosphere.

### Tomography and MOAO performance

UCSC astronomy graduate student Mark Ammons (PhD UCSC 2009) pursued the development and calibration of multiple laser guidestar wavefront measurement and tomographic reconstruction for MOAO correction. He made multiple advances that led to a successful demonstration of wide-field AO correction suitable for visible wavelength ($\lambda$ = 0.6 to 1.0 micron) science observing on a 10-meter class telescope. A full error budget consistent with that theoretically predicted for the Keck Next Generation Adaptive Optics system was demonstrated with actual measurements on the lab bench, lending credibility to the tomography approach being proposed for NGAO.

A chart of Strehl ratio across a 40x40 arcsecond field of view with laser guidestar tomography AO correction is shown in Figure 8. The 5 laser guidestar constellation is compared with a single laser guidestar, where anisoplanatic error dominates and significantly restricts the corrected field of view. Ammons developed the detailed error analysis that provides the characterization of expected performance, both on the bench and in a real AO system (Table 2). Note that although, because of scaling, ray angles are different on the lab bench than on the sky, the required metrological accuracy required in the lab experiment is as challenging as that required in a real telescope-based instrument. The demonstrated degree of accuracy makes Ammons' achievement uniquely relevant to the next generation multiple guidestar system designs.

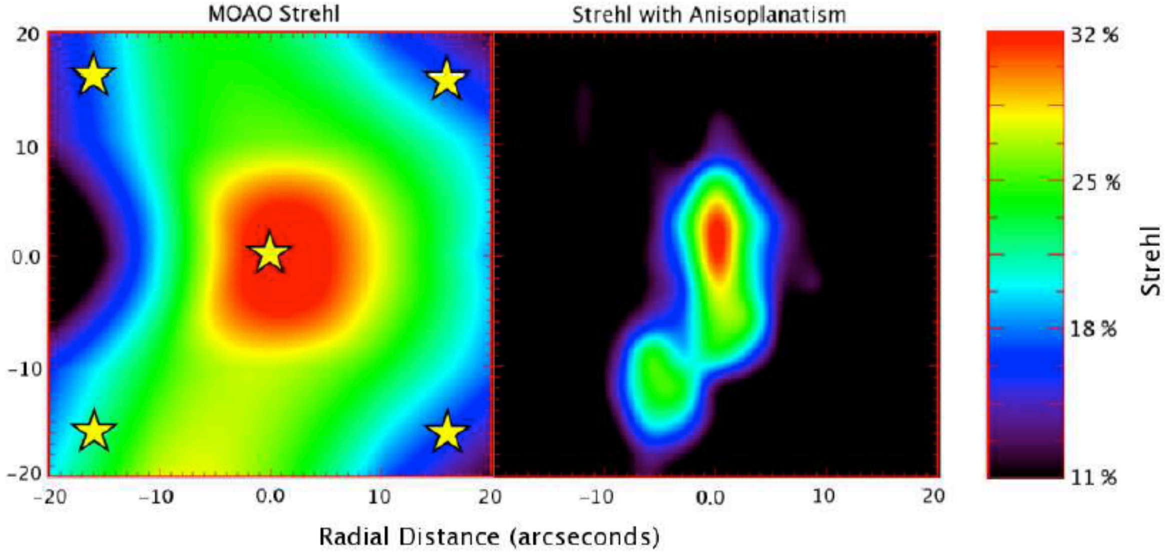


**Figure 7.** R-band (λ=0.65 μm) Strehl ratio as a function of field position over a wide field of view, measured on the testbed in MOAO configuration. Strehl ratio is a measure of the peak brightness of a point source (star) in the imperfect image as seen at the instrument focal plane, relative to peak brightness in an ideal image that had no optical or atmospheric aberrations (perfect Strehl ratio is 100%). On the left is the map of Strehl ratio using tomography with five laser guide stars, where Strehl ratios of greater than 25% are achieved over most of the 40x40 arcsecond field. On the right is the typical Strehl map for a single laser guidestar located in the center of the field, where anisoplanatims causes the Strehl ratio to degrade dramatically at angles more than 5 arcseconds off-axis.

**Table 2.** Error terms in the Multi-Object Adaptive Optics (MOAO) tomography demonstration experiments. Units are in nanometers ($10^{-9}$ meters). Strehl performance is shown for visible wavelengths ($\lambda$=0.65 μm)

| Error Budget Term | On-sky, On-axis | On-sky, Off-axis | Lab, On-axis |
|---|---|---|---|
| Fitting Error | 40.7 | 40.7 | 37.7 |
| WFS Aliasing | 16.2 | 16.2 | 15.0 |
| Tomography Error | 69.0 | 83.8 | 63.9 |
| WFS Systematic error | 41.5 | 41.5 | 38.5 |
| Field Stop Misalignment | 10.8 | 10.8 | 10.0 |
| PPM Lookup Table error | 32.4 | 30.0 | 30.0 |
| Static Uncorrectable | 48.6 | 45.0 | 45.0 |
| Scintillation | 12.6 | 12.6 | 11.7 |
| WFS Scintillation | 26.8 | 26.8 | 24.8 |
| Photon error | 16.2 | 16.2 | 15.0 |
| WFS zeropoint drift | 10.8 | 10.8 | 10.0 |
| Linearity calibration drift | 10.8 | 10.8 | 10.0 |
| Pupil registration drift | 25.9 | 25.9 | 24.8 |
| Total RMS | 118.2 | 127.3 | 109.5 |
| Predicted Strehl (%) | 33.5 | 28.1 | 33.5 |
| Measured Strehl (%) | 32.4 | 23.6 | 32.4 |
| Relative Error in Model | 3.3% | 16.0% | 3.3% |

Legend for Table 2:
WFS – Wavefront Sensor
PPM – Programmable Phase Modulator (the deformable mirror used in the testbed)
RMS – Root-mean square (square-root sum of squares of error terms in the list)

### *MCAO Closed Loop Algorithm Stability*

Graduate student Edward Laag (Earth Sciences, UC Riverside) led a project to show closed loop stability of Multi-Conjugate Adaptive Optics control algorithms. He used the LAO testbed in the MCAO mode of operation, that is, with closed loop measurement of wavefronts after correction by a series of deformable mirrors in the path at altitude-conjugate locations16.

Wind-predictive tomography. Graduate student Luke Johnson (Electrical Engineering, UCSC) is developing a wind-predictive controller applicable to tomographic AO. The real-time tomographic reconstructor maintains an estimate of the air turbulence at several representative layer altitudes. In this context, if the wind translation of these layers is predicted, some improvement in performance and relaxation of sensing requirements can result. On small time scales on the order of the wavefront sensing update rate (a few milliseconds), the turbulence changes are dominated by bulk flow of the air, rather than turbulent mixing, so a known wind velocity provides information useful to the tomography system.

Johnson has been experimenting with various wind motion prediction methods (the wind estimate updated every second or so), drawing from the extensive literature in the field of video image processing. Results from earlier experiments on the MCAO testbed were presented at the 2008 SPIE meeting17. The latest achievement (mid 2009) has been the development of fundamental theoretical derivations that 1) determine the limiting accuracy in predicting the wind speed from wavefront measurements (the Kramer-Rao lower bound) and 2) establish the maximum convergence rate (number of time steps needed in an iterative algorithm) to reach the said accuracy. Simulations have confirmed these limits and the next step is to confirm them with lab experiments using the LAO laser tomography testbed with its atmospheric turbulence plates. These results are being written in a paper to be submitted later this year, and will form a key component of Johnson's Electrical Engineering PhD thesis.

### *Atmospheric Turbulence Plate Development*

One of the key features of the MCAO/MOAO testbed from day one has been the ability to provide an input light beam that has aberrations equivalent to the optical effects of Earth's turbulent atmosphere. Optical phase plates provide these aberrations. They are manufactured to pre-specified characteristics that typical of the atmosphere. However, our earlier models have had imperfections that limited the dynamic range of aberration and introduced undesirable light scattering that interfere with the objectives of the test bed.

As new more complex AO systems are fielded on telescopes, the trend has been to incorporate on-board atmosphere/telescope simulators for assistance in alignment and calibration of the instrument and the control system. Thus the methods we have developed at LAO have wide ranging significance outside of the laboratory.

Physics graduate student Rachel Rampy worked with Dr. Sandrine Thomas and Laboratory engineer Daren Dillon to gradually perfect a method of fabricating optical phase plates that simulate the Kolmogorov spectrum of atmospheric turbulence over a wide dynamic range. Figure 8 shows a plate and a graph of a measured power spectrum.

A plate of this kind has been incorporated into the Villages optical AO experiment at Mt. Hamilton's 1-meter Nickel telescope (see the section below on Villages results). Here it is being used to not only to help tune the AO controller in off-line calibrations but also to provide a baseline theoretical atmosphere for comparison to the real atmosphere. The comparison provides insight in to how the real atmosphere departs from an ideal Kolmogorov model. Photos from the Villages run earlier this year are shown in Figure 9.

An aberrator plate of this kind will also be used to assist in the integration and testing of the Gemini Planet Imager as it is assembled at LAO next year. Rampy will stay on to participate in the GPI effort as a graduate student employee.

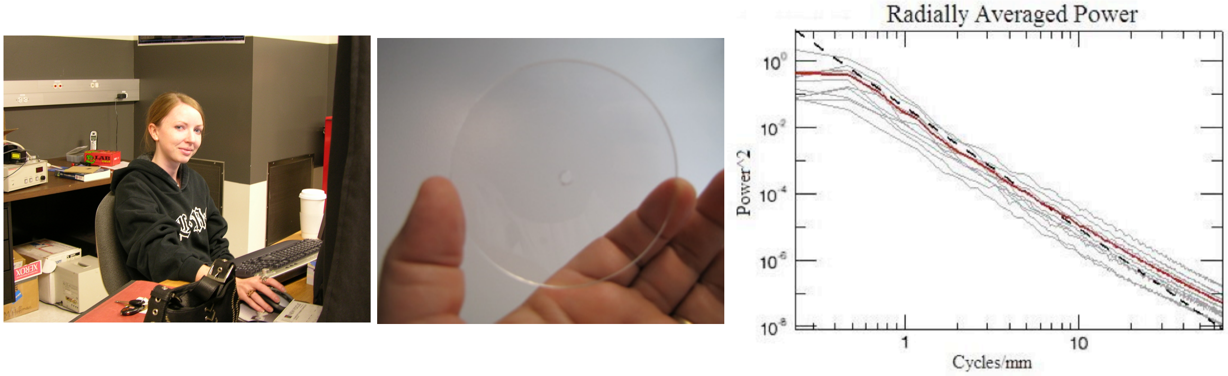


**Figure 8.** Physics student Rachel Rampy designed and fabricated phase aberration plates (one shown in the center photo) for use in the lab and in AO instruments for testing and calibration. The plate is nearly perfectly clear (as is the atmosphere) but exhibits the wavefront phase retardations that are characteristic of Kolmogorov turbulence. The graph on the right shows the match to theory over more than three decades of phase amplitude variation.

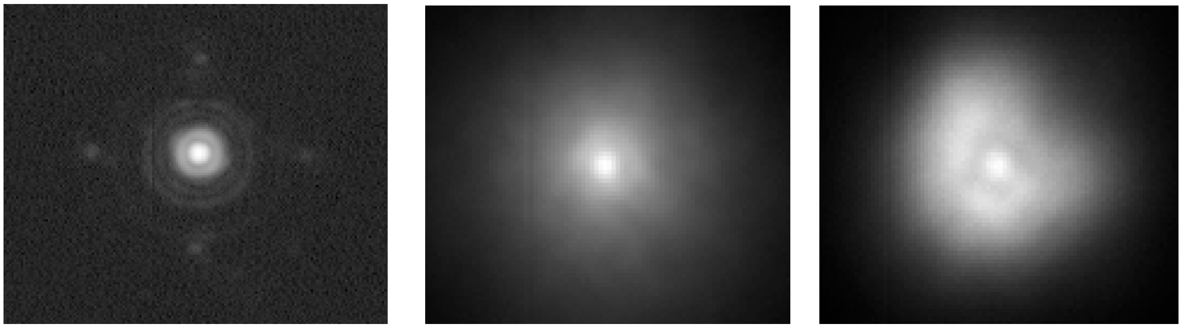


**Figure 9.** Star images from the Villages AO system. Left is an image of the unaberrated internal calibration source. This baseline image is limited only by the physics of diffraction. In the center is an AO-corrected image of the internal calibration source as aberrated by the phase plate, which is spinning to simulate wind-blown turbulence. One can see the diffraction-limited central core plus a halo of scattered light due to the residual phase aberrations of the "atmosphere." On the right is an AO-corrected image of an actual star (β Cygnus) viewed at λ=0.65 μm, also showing the diffraction-limited core and a scattered light halo. Images are logarithmically scaled to show details of the pattern of scattered light. Differences in the on-sky versus internal calibration data provide insight into the real atmosphere and telescope conditions at the observatory site.

### *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[12]. It is a modification of a concept based on the traditional knife-edge optical test. The aberrated light from the guide star is focused onto a quadrant of lenselets, splitting the light into four beams, each of which forms a pupil image. The bright and dark areas in the pupil images provide the information needed to determine the incoming wavefront phase. The pyramid sensor optical 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 obtainable in common commercially available lenslets. Astronomy graduate student Jess Johnson 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 the Laboratory. Johnson, and instrument specialist Renate Kupke, have performed simulations and predictions of pyramid-lenslet wavefront sensor performance with star light and have developed the appropriate wavefront reconstruction algorithms.[22]

The pyramid-lenslet sensor will be tested on-sky in the coming year, using the Villages AO system as the testbed.

### *Real-Time Tomography development*

The tomography algorithms needed to command multiple deformable mirrors given measurements from multiple laser guide stars have been developed in collaboration with members of the Center for Adaptive Optics under the auspices of its Adaptive Optics for Extremely Large Telescopes theme area. In 2004 LAO Director Donald Gavel presented a paper showing the derivation of 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[23,24].

Gavel and LAO computer engineer Marc Reinig, along with Electrical Engineering graduate students Carlos Cabrera, Matthew Fischler, and Ehsan Ardistani have since developed massively parallel architectures for implementing the real time MCAO and MOAO control algorithms[25]. Our group has programmed and tested prototype implementations of the tomography reconstructor using both field-programmable gate array (FPGA) simulators and an 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.

We are also now actively engaged with the Keck Next Generation Adaptive Optics project to further develop this architecture as the baseline for their MOAO system controller.[26] The concept of using massively parallel architectures for AO real-time control was first recommended to the TMT project by Donald Gavel in 2005, and it has subsequently been adopted as the baseline for TMT AO. TMT has contracted with a commercial vendor for a detailed concept design. We continue to be actively engaged in critiquing and making recommendations for this system.

### MEMS AO / Visible Light Laser Guidestar (Villages) Experiments

Laboratory development of MEMS and other new technologies naturally has lead to the next step, testing these technologies on a real telescope with starlight. In 2006, we proposed an experimental adaptive optics system for the Nickel 40-inch telescope at Mount Hamilton. A seed grant from the NSF Astronomy Division (Small Grant for Exploratory Research) with in-kind support from LAO allowed us to construct this system, dubbed "MEMS AO / Villages" – Visible Light Laser Guidestar Experiments. The apparatus was mounted for first light on the telescope in October 2007. The Phase 1 goals of Villages are the following:[27]

1) Demonstrate the feasibility of using MEMS deformable mirrors as wavefront correctors in an astronomical adaptive optics system in an observatory environment.[28]

2) Demonstrate MOAO operation (open loop control) on starlight, exploiting the MEMS inherent accuracy and the wavefront sensor calibration techniques we have developed in the Laboratory.[29]

MEMS AO / Villages successfully produced adaptive optics correction in the visible and near infrared wavelength science bands ($\lambda$ = 0.5 to 1.0 μm) with both the closed and open loop control configurations. Details of results from the observation runs from late 2007 and early 2008 were presented in our Year 6 annual report. These experimental demonstrations clear the path for an MOAO system implementation on a large telescope.

In Phase 2 of the Villages project, the plans are to incorporate a sodium laser beacon and use a MEMS deformable mirror to pre-correct the outgoing laser beam for the atmospheric turbulence in its up-link path. Up-path correction will concentrate the laser power into an extremely small spot in the sodium layer, approximately 10 times smaller in angular extent than current laser guide star spots, which will yield a profound improvement in the sensitivity of wavefront sensing. In particular, a factor of 10 reduction in spot size will decrease the laser power requirement by a factor of 100. This would dramatically reduce cost and risk for such systems, and could open the door to practical visible light laser guidestar systems on larger telescopes.

We plan to pursue this second phase in collaboration with two NSF funded programs in solid state sodium laser development, one at Lawrence Livermore National Laboratory and one at Lockheed Martin Coherent Technologies. These programs are expected to produce 5 to 10 Watt pulsed solid state lasers suitable for generating the artificial guide star.

## Summary of Milestones Accomplished August 2003 through August 2009

In summary, we highlight the following major technical milestones accomplished during the tenure of support from the Gordon and Betty Moore Foundation:

1. Constructed a forefront adaptive optics laboratory that will serve the needs of the University of California Observatories for decades to come.
2. Developed and demonstrated in the Laboratory the MEMS micromirror technology that will enable the high contrast adaptive optics for instruments that will image "exo-planets," planets orbiting other stars, and will enable the next generation of wide-field multi-guidestar AO systems.
3. Completed commissioning of the Villages instrument at the Lick Observatory, which demonstrates the suitability of MEMS deformable mirrors for astronomy and the feasibility of the multi-object AO open-loop control architecture.
4. Tested systems in the multiple guidestar tomography testbed that emulate the proposed Thirty Meter Telescope Adaptive Optics and the proposed Keck Next Generation Adaptive Optics systems, providing experimental validation of the computer predictions for tomography and wavefront sensing error terms[8]
5. Developed algorithms for measuring the bulk wind flow component of the turbulence and performed experiments on the LAO testbed demonstrating improvement in AO tomography using this information.

6. In collaboration with participating scientists, developed the apodized pupil Lyot coronagraph and demonstrated the level high contrast scattered light suppression required for the Gemini Planet Imager.
7. Published results on high contrast imaging with MEMS[6-11]
8. Published results on open-loop modeling and control of MEMS[3]

In line with our goals for becoming a research and teaching laboratory for the next generation of adaptive optics scientists, the LAO has:

1. Been the center of research projects for graduate students in Astronomy, Physics, Earth Sciences, and Engineering.
2. Graduated two LAO graduate research students with PhDs: Julia Evans (UC Davis, 2006), Mark Ammons (UC Santa Cruz, 2009), and expecting a third in September, Eddie Laag (UC Riverside, 2009). Three more LAO students have advanced to candidacy: Katie Morzinski, Luke Johnson, Jess Johnson (all from UCSC).
3. Hosted guest researchers from Jet Propulsion Laboratory (Amir Giveon), Lawrence Livermore National Laboratory (Bruce Macintosh and Brian Bauman), and the Space Telescope Science Institute (Remi Soumer).
4. Hosted two postdoctoral researchers: Renate Kupke and Sandrine Thomas (both of whom are now employed as UCO staff research scientists).
5. Worked with small companies to develop new AO technology by providing testing services and advice.
6. Hosted the laboratory component of the annual Adaptive Optics Summer School providing hands-on experience for attendees of this CfAO supported short-course. Attendees come from industry, academia, astronomical observatories, and other institutes world-wide that are using or developing adaptive optics.

## The Future of the Laboratory for Adaptive Optics

We are now fully transitioned to a permanent laboratory under the University of California Observatories, a multi-campus research unit within UC. This is one of three UCO laboratories, the other two being the UCO Instrument Laboratory and the UCO Detectors Laboratory.

The Moore Foundation grant was extended by one year (in a no-cost extension) because of our successes in attracting additional external support during the course of the grant. We received outside support from the National Science Foundation (NSF), Keck Observatory, Associated Universities for Research in Astronomy (AURA), NASA Ames Research Center, IrisAO Inc., and Microassembly Technologies Inc. We will continue to pursue similar levels of “soft” support in the out years in order to help offset constrictions in state funding in California.

We will continue our forefront role of advancing AO technology for astronomy. We will also be responsible for building and fielding new instruments. Notably, in the short term, these include the Gemini Planet Imager and the Shane Telescope Adaptive Optics system. In the longer term we will be playing a major role in deploying the Keck Next Generation Adaptive Optics system if it is successful in attracting the needed funding. In general we plan on leading roles in all AO instrumentation at UC Observatory telescopes and roles in partnership telescopes (Lick, Keck, TMT).

Our work has enabled a new wave of adaptive optics technologies that is now beginning to show an exciting payoff, evolving from idea to baseline architecture for next generation systems. For its first-light instruments, TMT (project started in 2003) is using traditional pre-LAO technology. However, we fully expect that the TMT infrared multi-object spectrograph and the high-contrast imager for planet formation studies, both follow-on instruments that are high priority for TMT science, will use MEMS technology and other techniques developed in the LAO. In the meantime, Keck NGAO (project started in 2006) is base-lining both MEMS and MOAO and will test these methods in major scientific instruments on a 10-meter telescope.

Another generation of adaptive optics technology advance is imminent. We envisage covering most or all of the visible wavelength spectrum with diffraction-limited imaging and spectroscopy, and giving access to the whole sky with laser guidestars, using small inexpensive MEMS deformable mirrors, compact cost-effective low power lasers, and optimally efficient wavefront sensors. This would revolutionize visible light astronomy and would significantly reduce the size and costs of instruments. The signal-to-noise ratio of astronomical exposures scales as telescope diameter to the fourth power with adaptive optics, as opposed to telescope diameter squared without AO, so science output in terms of detection and characterization of astrophysical parameters will be considerably more efficient with the valuable observing time on large aperture telescopes with adaptive optics than without.

Diffraction-limited capability at optical wavelengths will be highly beneficial to astronomical science. Today, these capabilities are provided by the 2.4-meter Hubble Space Telescope. However, Hubble has had its last servicing mission and is not expected to live more than another 10 years. We envision a progression of technology implementation similar to that of the current generation of infrared AO systems: first on 3-5 meter telescopes (e.g. Lick and Palomar), then on 8-10 meter (e.g. Keck), and ultimately on the Thirty Meter Telescope.

Adaptive optics success at earth-based observatories notwithstanding, there is also a strong potential for taking advantage of AO technology to improve spacecraft observatories. In particular, future space telescopes that image and characterize exo-planets will definitely require adaptive optics to correct for the tiny but increasingly significant slow variations of the spacecraft optics itself. Our plans to upgrade LAO's PSDI and coronagraph test lab to a higher level of accuracy and stability will mesh well with these future needs. We plan to continue our close collaboration with teams at NASA (both Ames Research Center and JPL) in order to test new concepts and components for space application.

## Laboratory for Adaptive Optics Research Staff

Affiliated with the Laboratory for Adaptive Optics are Principal Investigator Claire Max, Co-investigators Joseph Miller (recently retired) and Jerry Nelson, and Laboratory Director Donald Gavel. Additional research staff include:

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

**Marc Reinig** – Computers and electronics systems engineer.

**Renate Kupke** – Instrument Specialist, PhD in Astronomy. Experimentalist on the MCAO/MOAO testbed. Started at LAO as a post doctoral researcher, then hired into Lick Observatory as an instrumentation specialist.

**Sandrine Thomas** – Post doctoral researcher, PhD in Astronomy and Masters degree in laser technology. Experimentalist and analytic modeler for MCAO and ExAO. Recently hired into Lick Observatory as a research scientist.

**Bruce Macintosh** (part time research assignment from LLNL) – PhD Astronomer. Leader of the ExAO experiments and Principal Investigator for the Gemini Planet Imager.

**Brian Bauman** (part time research assignment from LLNL) – PhD Optical Engineer.

**David Palmer** (part time research assignment from LLNL) – Electrical and Computer Engineer. Project manager for GPI.

**Julia Evans** (guest and part time consultant) – UC Davis Graduate Student in Applied Physics, graduated with a PhD in 2006 and transitioned to postdoctoral researcher at LLNL. Performing experiments characterizing MEMS and high contrast imaging on LAO's ExAO testbed.

**Mark Ammons** (prior year's support by the Bachman fellowship) – UCSC Graduate Student in Astronomy. Performing experiments with MCAO/MOAO testbed on wavefront sensing and tomography. Graduated with a PhD in June 2009.

**Edward Laag** – Graduate student researcher, UC Riverside Department of Earth Sciences. Performed experiments with the MCOA/MOA testbed. Expects to graduate with a PhD in late 2009.

**Jess Johnson** – Graduate student researcher, UCSC Graduate Student in Astronomy. Performing laboratory experiments with pyramid wavefront sensing and AO control to be deployed and tested on the Villages experiment at Lick Observatory.

**Katie Morzinski** (supported in part by a NASA Michelson fellowship) – Graduate student researcher, UCSC Graduate Student in Astronomy. Performing experiments modeling and characterizing MEMS performance.

**Matthew Fischler** – Graduate student researcher, UCSC Department of Electrical and Computer Engineering. Designed, programmed and tested massively parallel computer architectures for MCAO/MOAO tomography. Graduated with Master's degree in 2007.

**Ehsan Ardistani** – Graduate student researcher, UCSC Department of Electrical and Computer Engineering. Testing concepts of massively parallel and pipelined computer architectures for MCAO/MOAO tomography.

**Bautista Fernandez** – Graduate student researcher, UCSC Engineering Department, Designing and testing new concepts for MEMS. Passed PhD qualifier exam in 2008.

**Luke Johnson** (supported by the Center for Adaptive Optics graduate fellowship) – Graduate Student in Electrical Engineering. Performing experiments on the MCAO testbed experimenting with dynamic predictive control algorithms. Passed his PhD qualifier exam in 2008.

**Andrew Norton** – BS Earth and Marine Sciences and now a graduate student in the UCSC school of Engineering. Characterizing MEMS performance.

**Rachel Rampy** – BS in Physics and first year graduate student in Physics. Designing and characterizing optical test plates for the MCAO and ExAO testbed.

**Donald Wiberg** – Emeritus professor of Electrical Engineering. PhD advisor to Luke Johnson and all-around consultant on matters of controls engineering for AO.

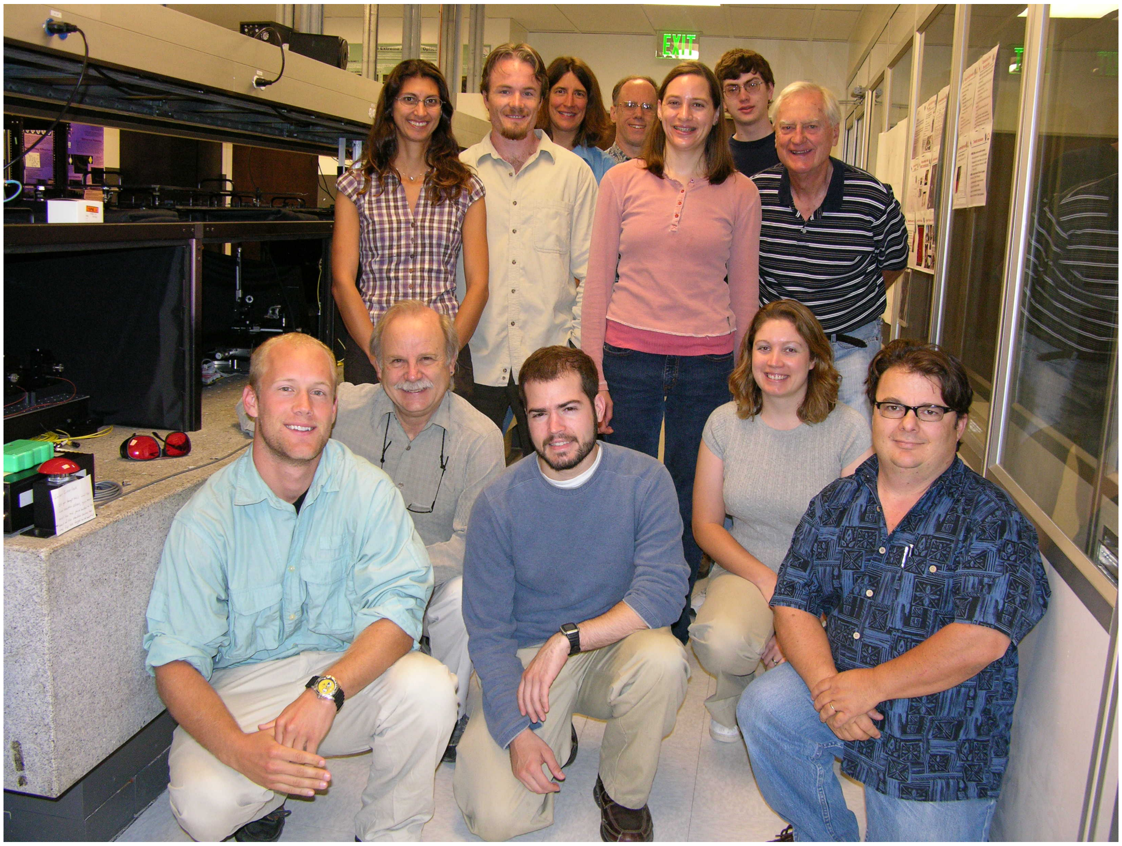


**Figure 10**. Laboratory for Adaptive Optics staff and researchers. Left to right, top row: Sandrine Thomas, Luke Johnson, Reni Kupke, Donald Gavel, Katie Morzinski, Carl Coker, Don Wiberg; bottom row: Andrew Norton, Marc Reinig, Mark Ammons, Julia Evans, Daren Dillon. This photo was taken inside the ExAO laboratory, with the ExAO testbed on the left and the cleanroom facility on the right.

## Financial Report

All funds were expended as of June 30, 2009. The final financial report will be submitted September 30, 2009 per our request for an additional 30 days preparation time for this report.

## Comprehensive List of LAO Publications

1. Macintosh, B., Graham, J., Palmer, D., Doyon, R., Gavel, D., Larkin, J., Oppenheimer, B., Saddlemyer, L., Wallace, J. K., Bauman, B., Erikson, D., Poyneer, L., Sivaramakrishnan, A., Soummer, R., Veran, J.-P., *Adaptive optics for direct detection of extrasolar planets: the Gemini Planet Imager*, **Comptes Rendus - Physique**, Volume 8, Issue 3-4, p. 365-373, (2007).
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*Planet Imager*, Advances in Adaptive Optics II, **Proceedings of the SPIE**, Volume 6372, (2006).

3. Morzinski, K., Gavel, D., Norton, A., Dillon, D., Reinig, M., *Characterizing MEMS deformable mirrors for open-loop operation: high-resolution measurements of thin-plate behavior*, **Proceedings of the SPIE**, Volume 6888, (2008).
4. Evans, Julia, Gary Sommargren, Lisa Poyneer, Bruce A. Macintosh, Scott Severson, Daren Dillon, Andrew I. Sheinis, Dave Palmer, N. Jeremy Kasdin, and Scot Olivier, *Extreme adaptive optics testbed: results and future work*, Advancements in Adaptive Optics, **Proceedings of the SPIE**, Volume 5490, (2004).
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