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

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

Submitted to the
Gordon and Betty Moore Foundation

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Executive Summary

The Laboratory for Adaptive Optics (LAO) has completed the sixth year of operation since the initiation of the Gordon and Betty Moore Foundation grant in August 2002. The goals of the Laboratory are to develop adaptive optics technology, concepts, and instruments for astronomy, with three main facilities: 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.

Within the Laboratory for Adaptive Optics, we have been able to pursue the higher risk experimental projects that otherwise would not have been funded by the giant telescopes. This has only been possible because of the independent nature of the funding for the Moore Foundation grant and is consistent with the Moore Foundation's goal of advancing cutting edge scientific research.

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

- We have **successfully deployed an on-sky experimental instrument designed to demonstrate several AO technologies that have been developed in the laboratory.** In October 2006, we received an NSF Small Grants for Exploratory Research (SGER) award for phase 1 of the Visible Light Laser Guide Star Adaptive Optics Experiments (Villages) project, which involves demonstrating the feasibility of MEMS deformable mirrors in an astronomical AO system. The Villages instrument was mounted to the 40-inch Nickel telescope at Mount Hamilton in November, 2007 and immediately began producing AO-corrected diffraction-limited images. Villages will continue to function as a testbed for on-sky demonstration of new technologies.
- The LAO is **playing a major role in the Keck Next Generation Adaptive Optics (NGAO) concept design**. We are working alongside researchers from the Keck Observatory and Caltech Optical Observatories to develop a multiple laser guidestar AO system for the Keck 10 meter telescope that will enable a wide variety of new high-resolution science covering 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 growth 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** passed critical design review (CDR) in April, 2007 with excellent ratings from the external review committee. The project is now in build phase. GPI assembly, integration, and test will take place at the LAO during 2009 and 2010, and first light at the Gemini South observatory is scheduled for early 2011. In 2005, the Gemini Observatory selected the team led by LAO researcher Bruce Macintosh to build GPI, which is 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 more than six orders of magnitude dimmer. Prototype experiments in the LAO ExAO testbed enabled the development of the technology and a successful proposal for this $22M instrument, furthering one of the main missions of the LAO.

- We've published **additional results from experiments on the Multi-Conjugate Adaptive Optics (MCAO) testbed**. Over the past two years we published results of tests with multiple guidestar tomography from the MCAO testbed in configurations representative of the next generation of wide-field AO instruments. This year we extended this work to incorporate prediction of wind-blown turbulence at multiple layers, we've established the long-term stability of closed loop tomography AO architectures, and performed experiments that validate system performance models and establish bottom-line error budgets for the Keck Next Generation AO system. Our team is collaborating with scientists from the Thirty Meter Telescope Project, Keck Observatory, and Gemini Observatory, all of which plan to install adaptive optics instruments using multiple laser guidestar tomography.
- **The LAO continues to be a training ground for graduate students and postdocs in astronomy and engineering.** Three astronomy graduate students are doing their PhD research in the laboratory leading to dissertations that will include instrumentation development as a major component in addition to observational astronomy research. Four engineering students are also conducting their PhD research in the lab. The LAO has hosted a number of visitors and students from industry, academia, and the CfAO sponsored summer school at UCSC.

The LAO core research staff includes two full-time research scientists, two full-time engineers, and one associate specialist. This year we hired Dr. Sandrine Thomas, who was a postdoctoral researcher, as our second research scientist. Eight graduate students (representing Astronomy, Physics, Earth Sciences and Engineering), and three half-time consulting scientists from Lawrence Livermore National Laboratory are also employed.

The broader AO and astronomy community has shown its keen interest in the LAO during its duration. 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 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 have continuing regular interaction with the TMT project team and have defined a number of our testbed experiments and component development efforts based on our discussions with them. Project manager Gary Sanders and AO manager Brent Ellerbroek are enthusiastic supporters of our efforts and regularly monitor our progress. Brent Ellerbroek served on the design review committees for the Villages project.

The National Science Foundation's Adaptive Optics Development Program (AODP), administered by the National Optical Astronomy Observatory (NOAO) is supporting 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:

- 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 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.

Sixth 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 Building located on Science Hill 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 laboratory has all 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)
- 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.
- Adaptive Optics specialized electronics development area
- Separate optical tables for individual 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

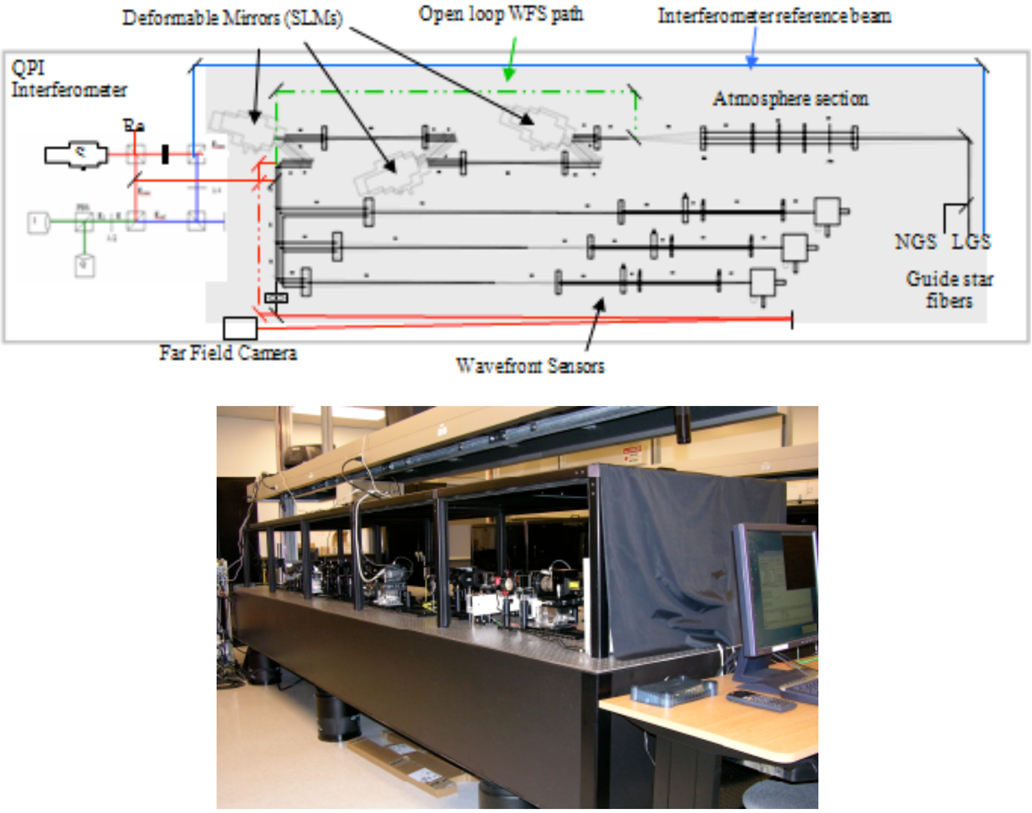


Figure 1. MCAO/MOAO Testbed showing major element and highlighting its reconfigurability for multiple guidestar wavefront sensors, closed loop (MCAO), and open loop (MOAO) architectures

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.

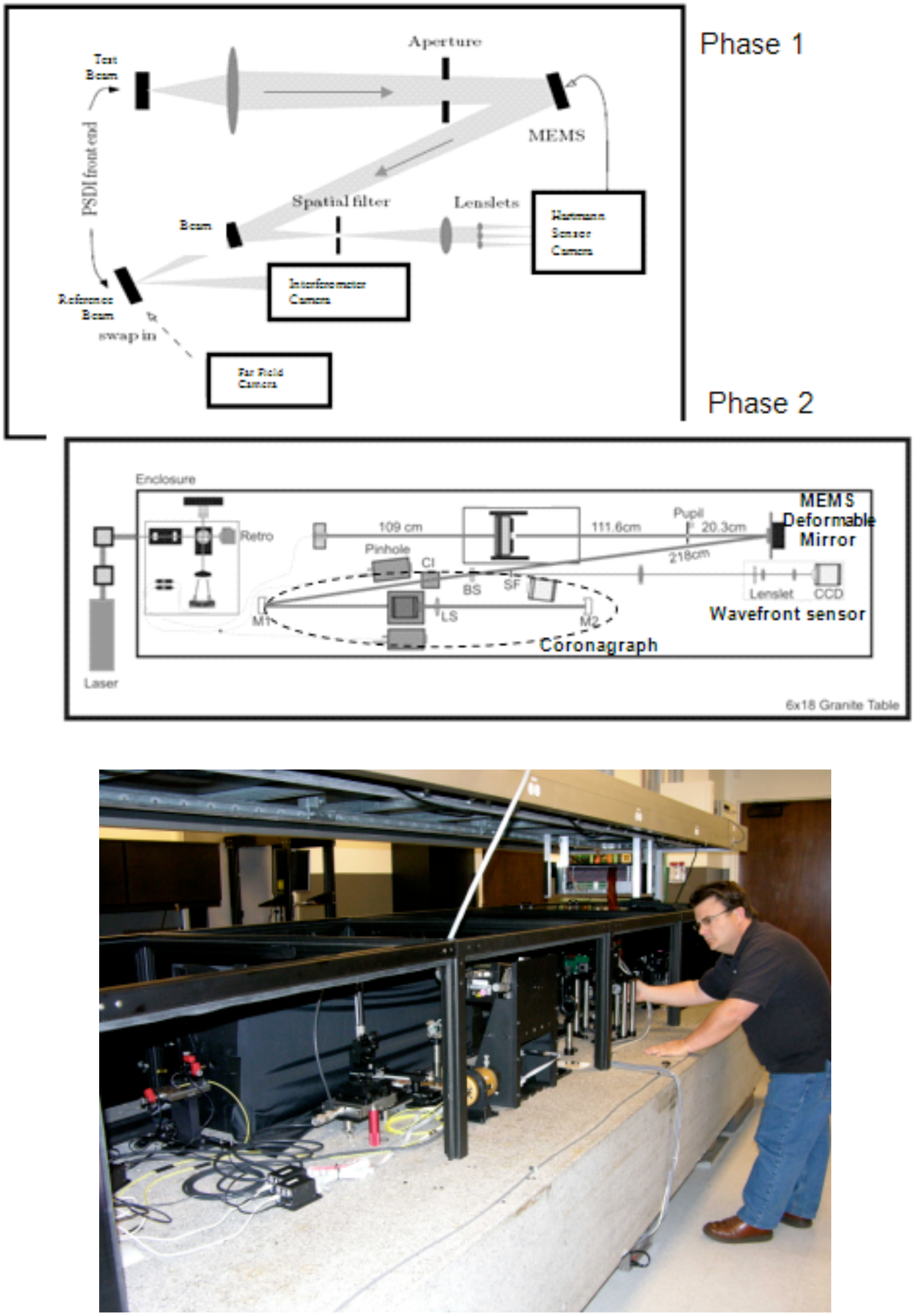


Figure 2. ExAO testbed progress from MEMS testing interferometer (Phase 1) to planet imager instrument prototype with diffraction-suppressing coronagraph (Phase 2).

Experiment Results: Extreme Adaptive Optics (planet imaging) testbed

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[1,2]. 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 ExAO testbed provides the prototype for both of these.

Here is a list of milestones accomplished to date using the 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 MEMS deformable mirror was controlled to a flatness of less than 1 nm rms and generated a high contrast ($<10^{-6}$) far-field image. This flatness has been routinely achieved with a number of 32x32 MEMS mirrors we now have in-house.
- 2005: MEMS deformable mirrors were controlled to “undo” the aberrations of a test aberrator plate down to less than 3 nm 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’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 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 our laboratory 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 is designed, fabricated, installed, and tested in the phase 2 arm of the ExAO testbed. Using the coronagraph we demonstrated 2×10^{-7} contrast over the field of view effective for planet imaging.
- 2008: The first 64x64 MEMS deformable mirror is delivered to LAO. The first version is “engineering grade” but we demonstrate <1nm flattening over a 16 mm area of this mirror. The “science grade” version of this device for installation into GPI is due to be delivered to LAO early next year.

MEMS 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 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 (Figure 3), but that no hysteresis is apparent on the ~0.5 nm level.

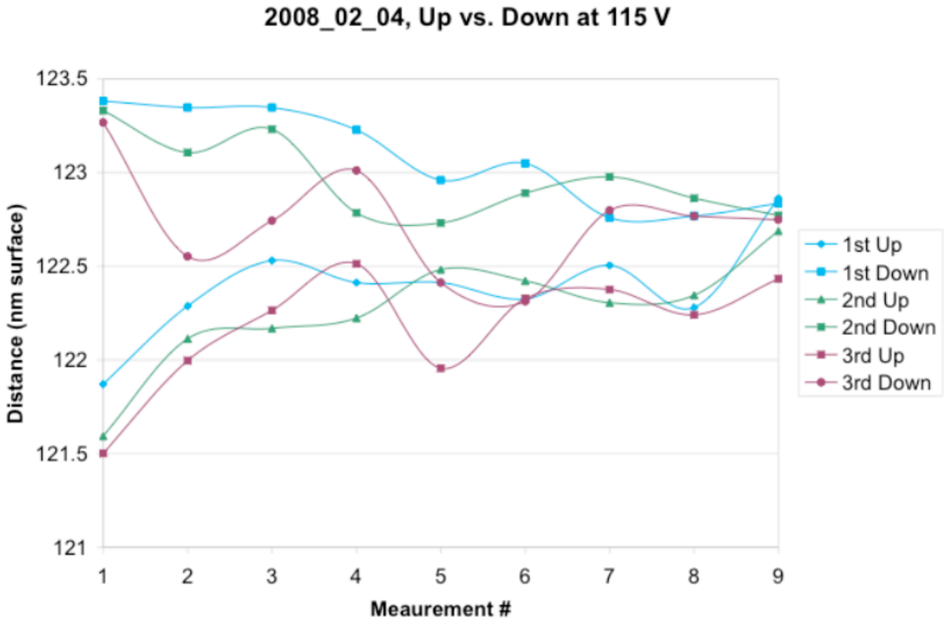


Figure 3. MEMS response measurements that appear to indicate 1.5-2 nm hysteresis actually are due to a slow response component (~1 minute decay time), which eventually settles to within the PSDI measurement noise. "Up" transitions are from 0 to 115 V and "down" transitions are from 180 to 115 V. Measurements on this graph are strobe samples spaced on 1/10 minute increments from the voltage transition time. Thus no hysteresis is indicated down to 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 an atmosphere. In anticipation of this need, we have proposed a new upgraded PSDI that would be smaller, stiffer, and would have a very precise temperature controlled environment. The result will be to significantly reduce the systematic error baseline of the wavefront flatness measurement, enabling up to a factor of 10 improvement in precision and suitable for testing coronagraphs and ExAO control to the level of $\sim 10^{-9}$ contrast.

MEMS device fabrication and testing

In 2005 we completed the 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 to meet our requirements[4].

We then initiated a contract 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 driven by needs solicited from the astronomical science community including consideration of 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 GPI subaward. We now have received our first engineering grade 64x64 devices for testing (Figure 4). 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 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.

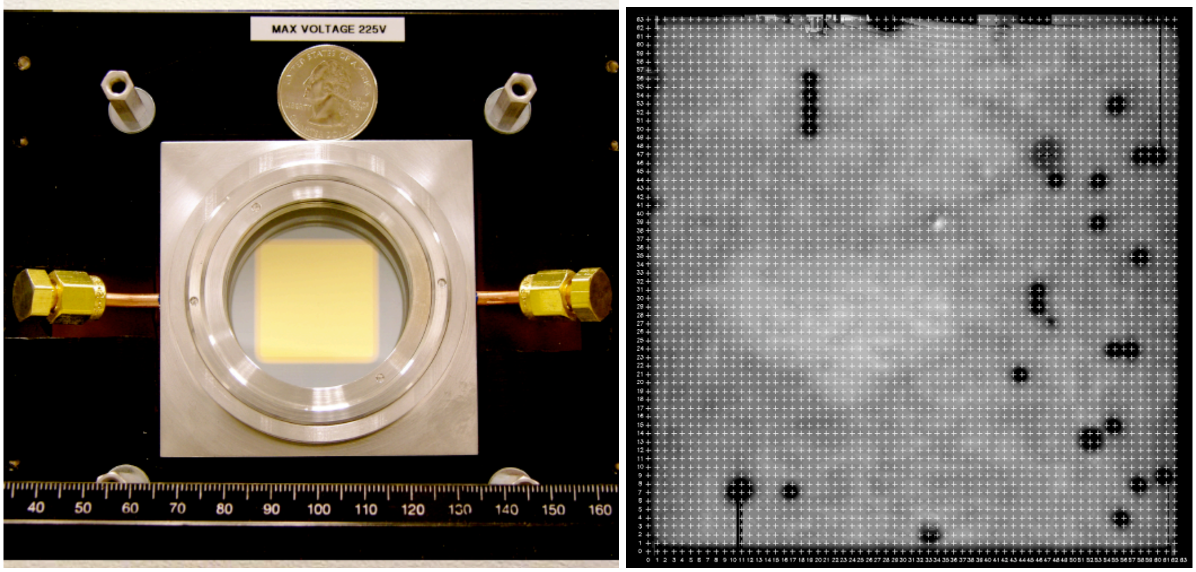


Figure 4. 4096-actuator engineering grade MEMS mirror recently delivered to LAO. Left: the device is shown in its protective chamber, with window and dry air ports. Right: a PSDI measurement of the flattened device, showing a number of dead actuators. A clear region of about 32 actuators across is available for further testing in the ExAO testbed. The contract requires delivery of a science grade device with 48 actuator diameter clear region.

Intensity aberration 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 and 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 have 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 that expected from the coronagraph optics. Independent tests of MEMS reflectivity have also confirmed the bounding to a few percent variation.[6,7]

Coronagraph contrast measurements

In earlier testing, prior to the phase 2 upgrade with full coronagraph, we used 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 area[8-11]. With the addition of the coronagraph are we can now demonstrate a dark discovery region that surrounds the star.

In June 2007 we received the parts for our custom designed apodized pupil Lyot coronagraph[12] (Figure 5). The pupil apodizer and focal plane stop work together to suppress diffraction rings within the discovery region that would otherwise be produced by any sharp-edged coronagraph elements. ExAO testbed results are shown in Figure 6, showing that we are achieving the expected contrast enhancements. Our next steps will be to test this system in combination with the MEMS in the path and with MEMS correcting artificial atmospheric turbulence in the testbed.

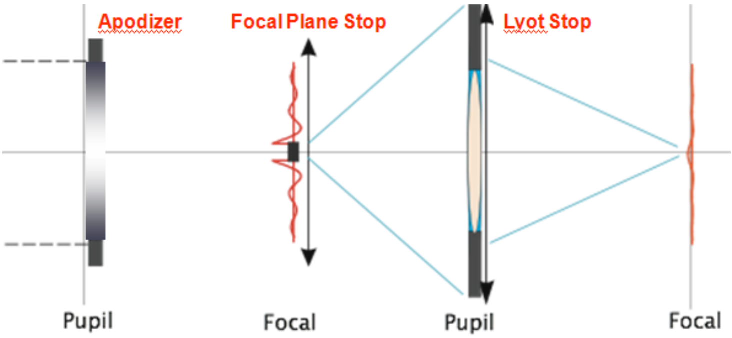


Figure 5. Layout of the apodized Lyot coronagraph.

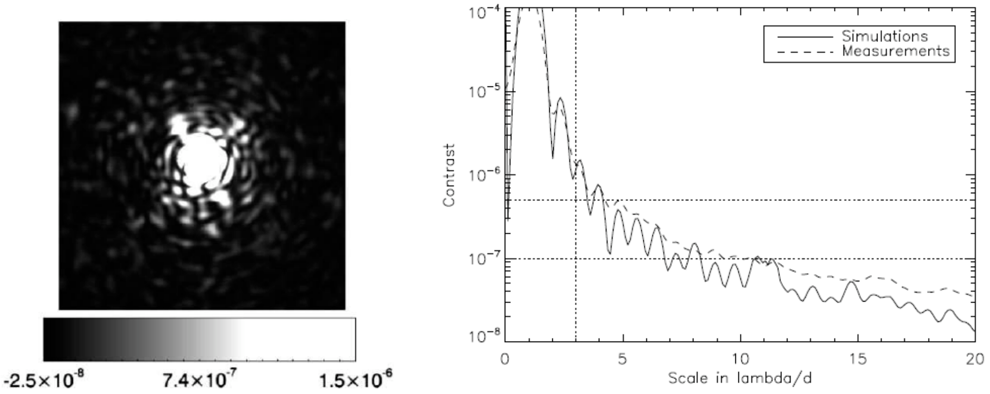


Figure 6. Left, image in the focal plane of the scattered light from the star leaking through the apodized pupil Lyot coronagraph. The scale is log-stretched. Right: lineout of contrast, showing that the coronagraph's suppression of diffracted light exceeds 10^6 at 3 λ/D and $5x10^7$ at 5 λ/D. These suppressions are two orders of magnitude more than that of the standard Lyot coronagraph (we reported results on this in our Sept. 2006 report).

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 technically useful results through demonstrations of tomographic wavefront sensing and multi-conjugate wavefront control.

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 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.

Table 1 shows the MCOA testbed configurations for which we have published 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 cutting-edge requirements for low residual wavefront error and a correction suitable for the shorter wavelength bands.

	System	Telescope Diameter	Pupil sampling	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

Table 1. MCAO Testbed configurations and tests.

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 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. 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 several selectable small fields which is suitable for a multi-slit spectrometer or multiple unit integral field spectrometer. The later is the idea behind TMT IRMOS and for the proposed Keck dIFS instrument.

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 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 – 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.

Incorporation of a woofer-tweeter control. Astronomy graduate student Mark Ammons and Electrical Engineering graduate student Luke Johnson added a new deformable mirror to the MCAO testbed this year. This low order membrane mirror ("woofer") has 51 degrees of freedom and a large stroke (surface deformation range up to 50 microns). This accomplishes two goals: 1) it allows the remaining high-order mirrors ("tweeters," our spatial light modulators) to operate within their dynamic range without phase-wrapping, and 2) it directly models the same woofer-tweeter configuration envisaged for the Keck NGAO system[15]. Prior testbed experiments had a large component of error due to diffraction when the spatial light modulators had to wrap phase. This upgrade therefore allows the finer control needed to test to NGAO's precision.

MCAO stability. Graduate student Eddie Laag (Earth Sciences, UC Riverside) led the effort to show closed loop stability of Multi-Conjugate Adaptive Optics control algorithms. He used the 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 locations. Eddies' paper reporting these results was accepted for publication in JOSA-A this year[16].

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. Luke 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 experiments on the MCAO testbed are shown in Figure 7 and were presented at an SPIE meeting this year[17].

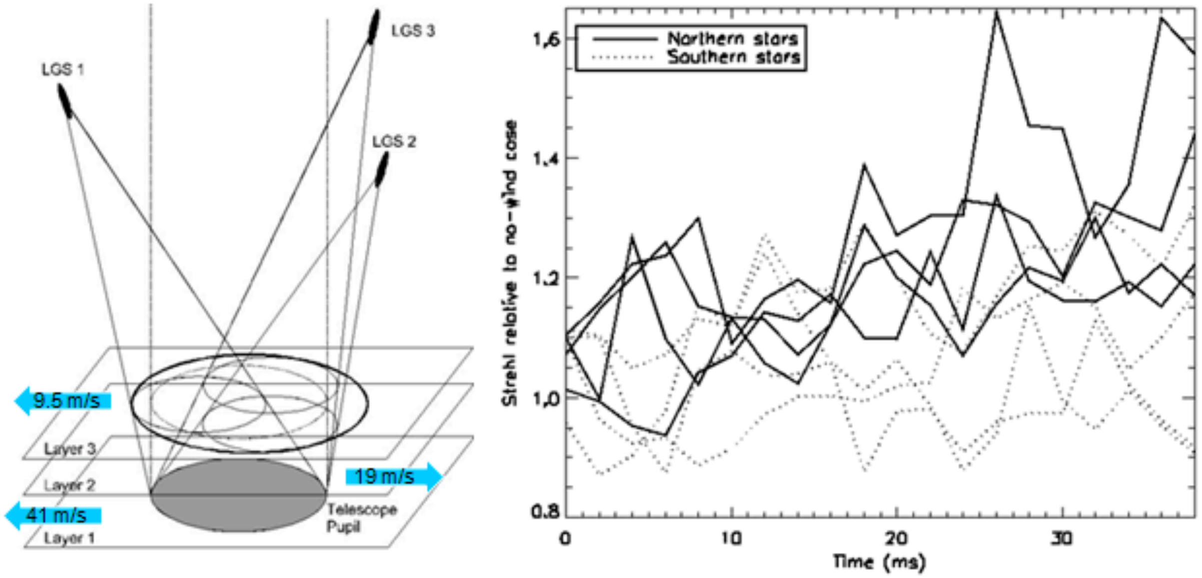
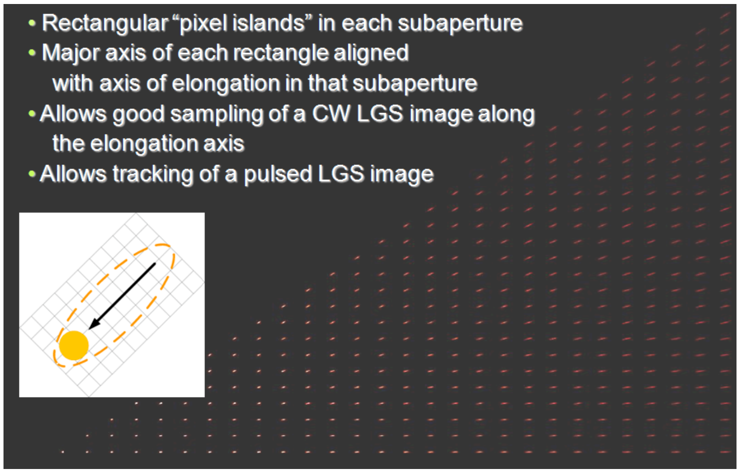


Figure 7. MCAO tomography is improved with bulk wind prediction on a layer by layer basis. The curves show that as time progresses, repeated measurements of the volume improve in accuracy if we know the shifted positions of the layers. “Northern” stars (solid lines) are mostly downwind of the guidestar constellation, so well-measured and predicted turbulence is blowing across their beams, whereas upwind stars are more affected by newer unpredicted components of turbulence.

Elongated laser guidestars with Hartmann wavefront sensors. An artificial guidestar beacon is created by projecting a laser beam which fluoresces in the mesospheric sodium layer. Using a laser beacon vastly enlarges the portions of the sky over which astronomers can use adaptive optics, hence lasers are essential to future generation AO systems. However, such a guidestar has properties that differ significantly from those of a natural star. In particular, the star is a finite distance away (with a mean distance of 90 km compared to essentially infinity for stars), and also the star light comes from a finite range of altitudes, 85-95 km roughly. These two combine to both blur the guidestar and to change its shape within the wavefront sensor selectively depending on Hartmann subaperture location within the aperture. A typical pattern of Hartmann spots from a laser are depicted in Figure 8. Furthermore, the distribution of return signal versus altitude varies as the mesospheric sodium layer has dynamic changes in its mean height and distribution of sodium. Some representative data from off-axis observations of the Lick Observatory laser beacon are shown in Figure 9. These variations start to become very important as the telescope apertures get larger. For example, the depth of focus for a 30 meter telescope is only about 10 meters, so sodium mean altitude shifts of only a few meters will result in severe degradation of the adaptive optics correction. Our measurements indicate that resets to focus, based on natural stars, must be done on time scales of the order of a few times a second (Figure 10).



- Rectangular "pixel islands" in each subaperture
- Major axis of each rectangle aligned with axis of elongation in that subaperture
- Allows good sampling of a CW LGS image along the elongation axis
- Allows tracking of a pulsed LGS image

Figure 8. A simulated Hartmann pattern for a laser guidestar as it would appear on one section of a Keck NGAO system wavefront sensor. Each spot is an image of the guide star as sampled by a small subregion of the 10 meter telescope aperture. Images from sub apertures separated far from the laser projector show greater distortion due to the finite depth of the sodium layer (an elongation). One means of mitigating this is to use a specialized sensor geometry, depicted in the inset.

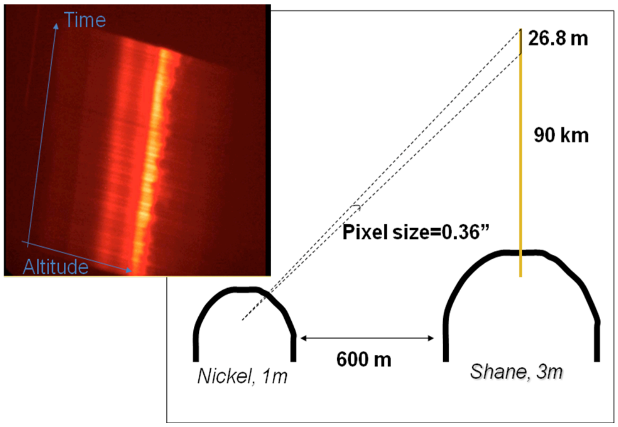


Figure 9. Variation of the mesospheric sodium density as a function of time and altitude was measured using the Lick Observatory Shane Telescope sodium laser. Drift-scan images from the Nickel, 600 meters to the west, enable us to resolve time and altitude dependence.

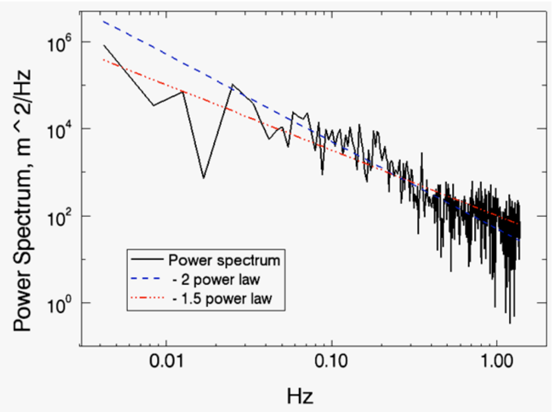
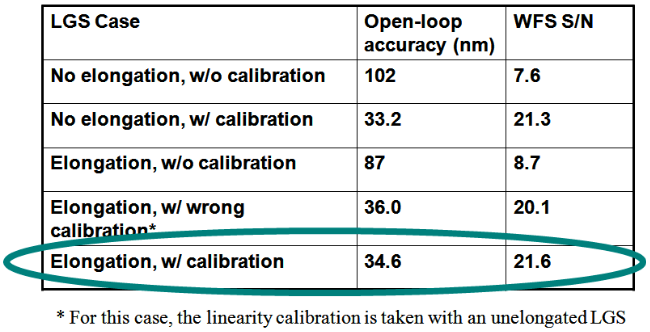


Figure 10. Power spectrum of sodium mean height variations. The standard deviation of mean height is tens of meters per second, a concern for larger aperture telescope AO systems that depend on laser guidestars for focus control.

Postdoctoral researcher Sandrine Thomas has published a number of papers describing optimal wavefront sensor design given seeing conditions and signal strength.[18-20] She has added a study of the elongated laser spot[21], and is now studying the options of tracking the sodium variability to improve wavefront sensing accuracy. This work is being done in collaboration with TMT researchers who want to understanding the limits to laser guidestar wavefront sensing and with Sean Adkins at Keck observatory who is leading the development of a specialized CCD sensor where the goal is to optimally sample the laser guidestar pattern.

Astronomy graduate student Mark Ammons has simulated the laser guidestar variations on the MCAO testbed, and re-calibrated the Hartmann wavefront sensors to account for them. His results show that with the linearity re-calibration there is no degradation of performance due to spot shape variation (Figure 11). However, there is one crucial aspect that we do not presently have the capability to measure on our testbed: error due to photon noise. For that we need a much more sensitive photon-counting detector in the wavefront sensor. Such devices have recently become available at reasonable cost so we plan to add one to our laboratory next year. With this we will perform photon-limited experiments with both the laser guidestar simulator and also to test the photon-limited performance of the pyramid wavefront sensor.



LGS Case	Open-loop accuracy (nm)	WFS S/N
No elongation, w/o calibration	102	7.6
No elongation, w/ calibration	33.2	21.3
Elongation, w/o calibration	87	8.7
Elongation, w/ wrong calibration*	36.0	20.1
Elongation, w/ calibration	34.6	21.6

* For this case, the linearity calibration is taken with an unelongated LGS

Figure 11. Results of tests on the MCAO testbed determining the effects of laser spot elongation on the linearity of the wavefront sensing.

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 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. 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 our laboratory. Jess, and instrument specialist Renate Kupke, have performed simulations and predictions of performance with real star light and have developed wavefront reconstruction algorithms.[22]

We are now in a position to test the pyramid-lenslet sensor on-sky, using the Villages AO system as the testbed (see below for an update on Villages). The sensor is scheduled to see first light during our September 2008 observing run.

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 and Matthew Fischler, 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 FPGA simulators and 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.

We are also now actively engaged with the Keck Next Generation Adaptive Optics project to further develop this architecture as the baseline for their MCAO 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, however we continue to be actively engaged in critiquing and making recommendations for this system.

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.

In August 2006 we applied to the NSF Astronomy Division for a $200K Small Grant for Exploratory Research to take an experiment to the Nickel 40-inch telescope at Mount Hamilton. This grant was awarded, and with leveraging support from the UCO/Lick Observatory and the LAO we subsequently designed and built a system we've designated as Villages – Visible Light Laser Guidestar Experiments. The system has now been successfully tested on-sky and has achieved the first two objectives of this program:[27]

1) Demonstrating the feasibility of using MEMS deformable mirrors as wavefront correctors in an astronomical adaptive optics system in an observatory environment.[28]
2) Demonstrating the unique ability of MEMS deformable mirrors in combination with our calibrated Hartmann sensors to work accurately in an open-loop control configuration with real starlight and typical atmospheric turbulence conditions.[29]

In observation runs starting in October 2007, MEMS AO / Villages clearly produced 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 clears the path for an MOAO system on a large telescope.

The configuration of the experimental instrument is shown in Figure 12. The system is 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.

Results from the Villages observation runs in late 2007 and early 2008 are shown in Figures 14 through 16.

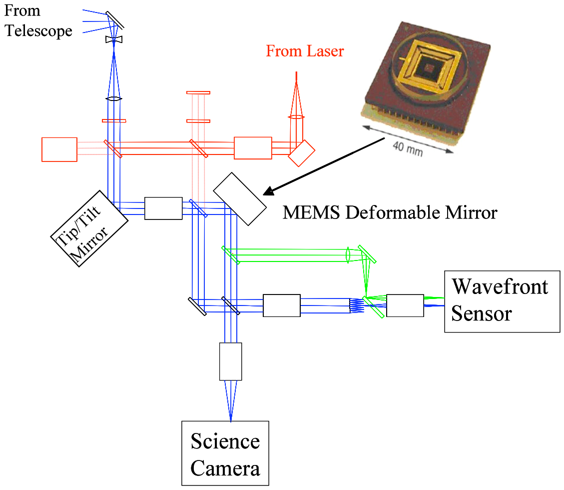


Figure 12. MEMS-AO / Villages system. The system employs a 140 actuator MEMS deformable mirror and fits on the back of the Lick Observatory 40-inch Nickel telescope.

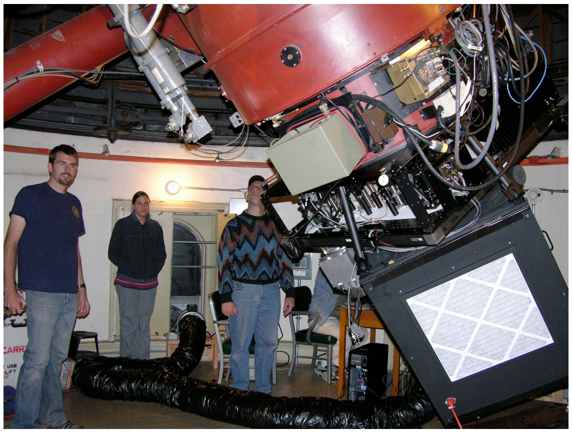


Figure 13. MEMS-AO / Villages mounted to the Nickel telescope.

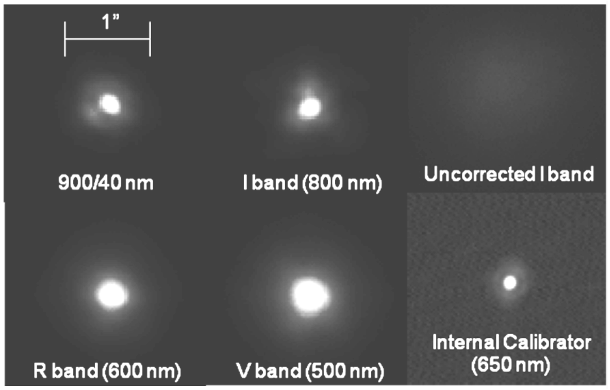


Figure 14. Test images of stars in the various visible astronomical bands. The internal calibrator source is a diffraction-limited beam from a laboratory laser. Uncorrected star light is spread over a 1 arcsecond region, while corrected light has a core of 0.2 to 0.3 arcseconds depending on wavelength, about a factor of 5 improvement. The AO-corrected telescope resolution depends on telescope aperture diameter, so a 10 meter telescope with this same level of correction would produce a factor of 50 improvement in image resolution.

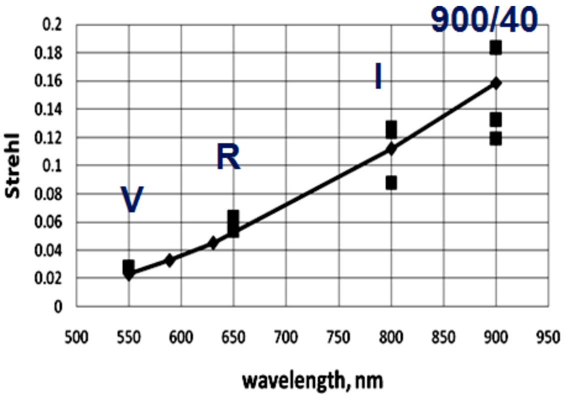


Figure 15. Performance of the AO correction in each astronomical band. Strehl is a normalized measure of correction fidelity (on a scale of 0 to 1) that is applicable to any diameter telescope.

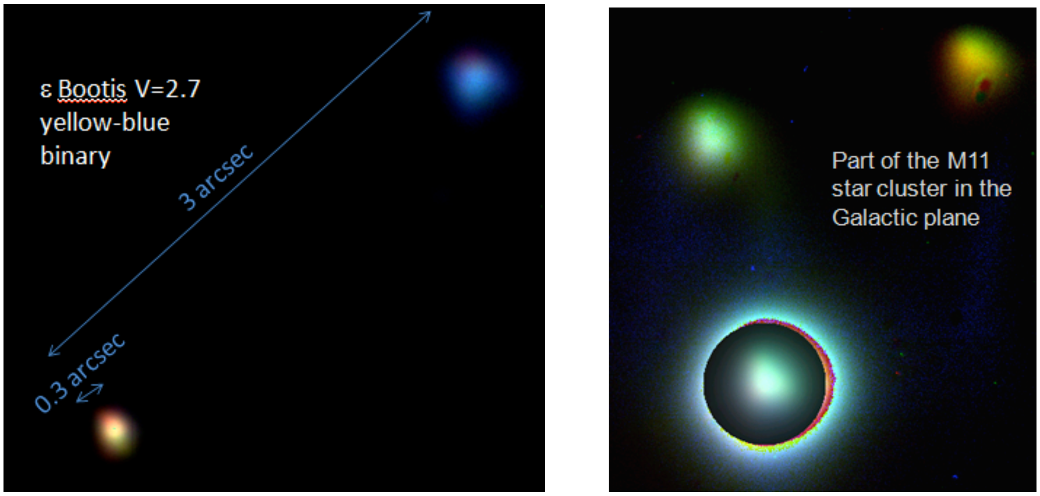


Figure 16. Colorful images of star clusters with the Villages system, demonstrating the sharpened images after adaptive optics correction. These are “true color”: red = R band, green = V band, blue = B band filter. On the right image, we show the bright star with the central core brightness suppressed so as to bring up the brightness of the background companion stars and nebulosity. This image also shows the residual ~ 1.0 arcsec seeing halo surrounding the 0.3 arcsec core of the bright star. This gives an idea of the Villages AO resolution improvement over uncorrected seeing (which scatters some of the light into the halo).

In Phase 2 of this project we plan to incorporate a sodium laser beacon. The plan is to project the laser from the primary aperture of the 1-meter telescope and to use adaptive optics pre-correction of the beam for the atmospheric aberrations (red lines in Figure 12). This will concentrate the laser power into an extremely small spot in the sodium layer, approximately 10 times smaller in angular extent than current LGS spots, which will have a profound effect on 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.

We plan to pursue this second phase (first light ca. 2009) 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 expect to have 5 to 10 Watt pulsed solid state lasers ready in this time frame.

Summary of Milestones Accomplished Sept. 2007 through Aug. 2008

In summary, we have accomplished the following major milestones:

1. Completed commissioning of the Villages instrument at the Lick Observatory Nickel telescope. Demonstrated the practicality of MEMS deformable mirrors for astronomy. Demonstrated on-sky AO correction with open-loop control.
2. Tested configurations in the MCAO testbed relevant to the Keck Next Generation Adaptive Optics project , validating theoretical models for tomographic atmospheric measurement and wavefront compensation[8] Demonstrated the improved performance attained with look-ahead prediction of wind-blown turbulence.
3. Tested the apodized pupil Lyot coronagraph using the phase 2 arm of the ExAO testbed, demonstrating high contrast over a large field.

4. Diagnosed beam intensity and reflectivity issues as they relate to high contrast imaging, using the ExAO testbed.
5. Published additional results on high contrast imaging with MEMS[6-11]
6. Published additional results on open-loop modeling and control of MEMS[3]

The Future of the Laboratory for Adaptive Optics

We have requested and been approved for a one year no-cost extension to the original grant. Because of successes in finding additional outside funding during the course of the grant, we have been able to stretch our spending such that an additional 12 months of operation beyond the original 6/30/08 completion date can be accomplished using the remaining Moore Foundation funds.

In 2008-9 we plan to achieve the following list of milestones:

1. In concert with NSF and CfAO support, deploy a laser guide star with the Villages system and demonstrate novel techniques for efficient guide star wavefront sensing.
2. Continue to work with Keck Observatory to develop their Next Generation Adaptive Optics System. In particular, perform risk-reduction experiments on the MCAO testbed and develop prototypes for high efficiency wavefront sensors and the real-time tomography compute engine.
3. Test the pyramid wavefront sensor on the sky with the Villages experiment.
4. Complete the testing of the 64x64 MEMS deformable mirror in concert with the apodized Lyot coronagraph on the ExAO testbed and prepare for assembly and laboratory testing of the final GPI instrument.

The major programs we are pursuing are listed below:

- GPI commitment
- NSF MRI/ATI-funding of the laser guidestar development with Villages as the testbed
- Keck NGAO major role in component development/testing/construction
- Ever-larger role in TMT adaptive optics design and component development
- Major role in the TMT IRIS instrument (integral field spectrograph instrument to be fed by the AO corrected beam)

Our work has enabled a new wave of adaptive optics technologies which are now beginning to show an exciting payoff, evolving from idea to baseline architecture for next generation systems. For example, TMT (project started in 2003) is sticking with traditional pre-LAO technology for first-light AO, but Keck NGAO (project started in 2006) is base-lining MEMS and MOAO. We fully expect that the 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.

Yet another generation of adaptive optics technology advance is eminent. We envisage covering the complete 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 as well as significantly reduce the size and costs of instruments. The signal-to-noise 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 all the optical wavelengths is clearly beneficial to astronomical science. Visible light AO down to 330 nm wavelength (the atmospheric cut-off) at high Strehl would effectively replace Hubble's capability, and with the larger aperture telescopes on the ground, well exceed it. We envision a progression of technology implementation similar to that of the infrared AO systems: first on 3-5 meter (Lick and Palomar), then on 10 meter (Keck), and ultimately on the 30 meter.

Laboratory for Adaptive Optics 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 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.

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 (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.

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.

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.

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

Matthew Fischler – Graduate student researcher, UCSC Engineering Department. Designing, programming and testing massively parallel computer architectures for MCAO/MOAO tomography. Graduated with master's degree in 2007.

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

Andrew Norton – BS Earth and Marine Sciences and applying to UCSC graduate school in engineering. Characterizing MEMS performance.

Rachel Rampy – BS in Physics and entering graduate school in Physics. Designing and characterizing optical test plates for the MCAO and ExAO testbeds

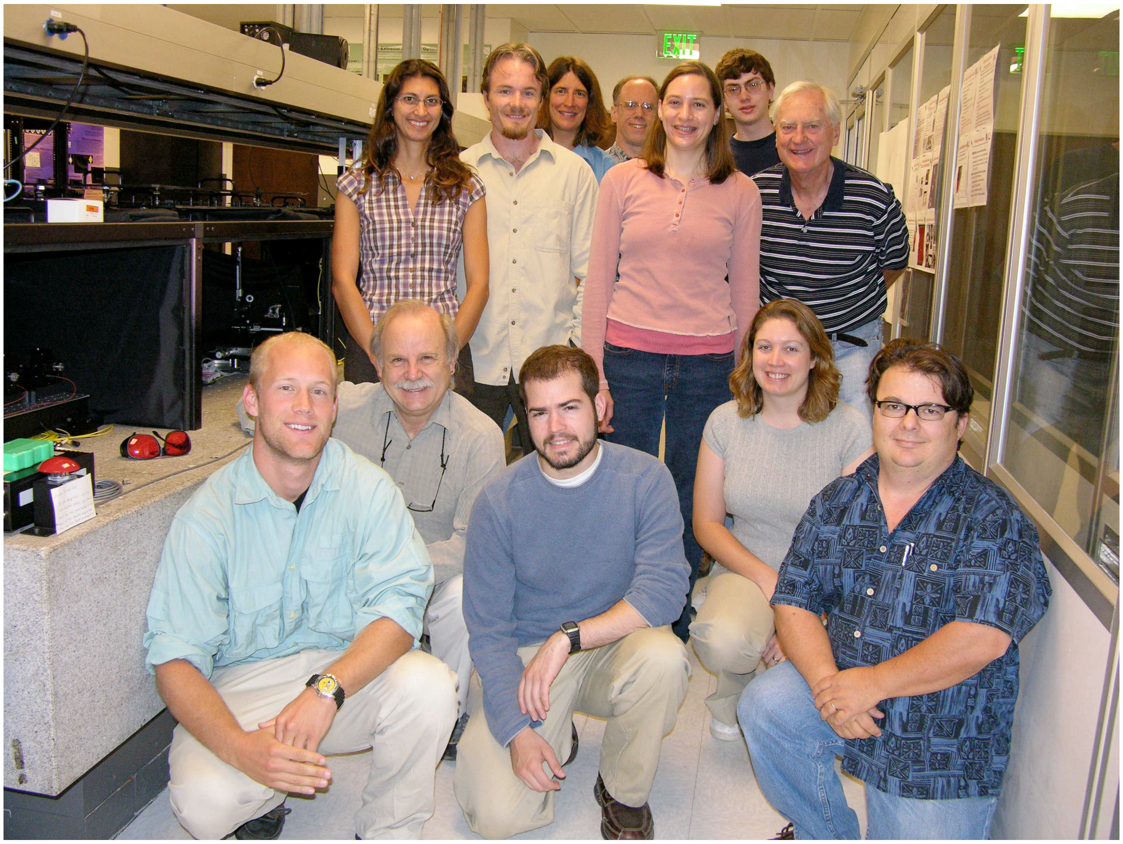


Figure 17. Laboratory for Adaptive Optics staff and researchers. Left to right, top row: Sandrine Thomas, Luke Johnson, Reni Kupke, Donald Gavel, Katie Morzinski, Carl Coker, Don Wiberg; bottom row: Andrew Norton, Marc Reinig, Mark Ammons, Julia Evans, Daren Dillon. This photo is taken inside the ExAO laboratory, with the ExAO testbed on the left and the cleanroom facility on the right.

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