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

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Executive Summary

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

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 five:

- We have **completed the construction of an on-sky experimental instrument that will 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. This on-sky experiment, mounted to the 40-inch Nickel telescope at Mount Hamilton, will also be a testbed for on-sky demonstrations of the spatially filtered Hartmann wavefront sensor and the pyramid-lenslet wavefront sensor, both of which were invented by LAO researchers. The instrument is now in final integration and testing in the LAO cleanroom and is scheduled to be taken to the telescope in late September, 2007.
- 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 executive committee.
- The **Gemini Planet Imager (GPI) project** passed preliminary design review (PDR) in May, 2006 with an excellent ranking from the external review committee. The project was recommended to immediately begin CDR (Critical Design) phase with detailed design and costing to be completed by May, 2008. GPI assembly 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, the Gemini Planet Imager (Extreme Adaptive Optics Coronagraph) for the Gemini Observatory which is designed to image and characterize planets outside our own solar system. Initial experiments at the LAO led to a successful proposal for this $22M instrument, marking a major milestone in accomplishing one of the main missions of the LAO.

- We published **additional results from experiments on the Multi-Conjugate Adaptive Optics (MCAO) testbed**. Last year we published our multiple guidestar tomography measurements. This year we extended this work to a larger constellation of guidestars and a field of view representative of the next generation of wide-field AO instruments. In addition, we established the long-term stability of closed loop MCAO architectures, something that is impractical to do with computer simulations because of the complexity of the system. Our team is collaborating with scientists from the Thirty Meter Telescope Project, Keck Observatory (see Keck Next Generation Adaptive Optics, above), and Gemini Observatory.
- **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. Three 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. This summer we mentored two highly capable undergraduate intern students who acquired significant laboratory skills while also providing valuable contributions in the testing of new AO components. James Ah Heong from University of Hawaii, Hilo tested the first prototype segmented MEMS deformable mirrors produced by the Iris AO corporation. Abubakarr Bah from Santa Rosa Junior College (transferring to UCLA this fall) tested new microlenslet arrays destined as an upgrade for the Keck adaptive optics system.

The LAO core research staff includes one full-time research scientist, two full-time engineers, and one associate specialist (one of our postdocs was promoted this year). We also supported one postdoc from France, seven graduate students (representing Astronomy, Earth Sciences and Engineering from UCSC and UCR), and four half-time consulting scientists from Lawrence Livermore National Laboratory. Visiting scientist David LeMignant from Keck Observatory has been here for a one-year sabbatical continuing through August, 2007. David is the AO instrument scientist at Keck and is actively engaged in planning for the Keck NGAO project.

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.

Fifth Year Status Report

Research Facilities Status

In July 2006, LAO took possession of five additional office spaces totaling 846 square feet in the Thimann Building across the corridor from our laboratory. Four of these offices house the LAO core research staff with the fifth space dedicated to additional lab support activities. LAO now consists of a total of 2,891 square feet on Science Hill, located close to the UCO/Lick Observatory facilities, the UCSC Astronomy Department, and the Center for Adaptive Optics (CfAO) on the UC Santa Cruz campus. The laboratory has environmental systems to control temperature, dust, lighting, humidity, and vibration to acceptable levels, which are crucial for the precise optical measurements performed there.

Building	Room Number	Assignment	Square Feet
Thimann	185	MCAO Lab	776
	191, 191A	EXAO Lab	704
	191B, 191C	Clean room & dressing area	414
	103	Lab area with microscopes	147
	105B	3 person office	224
	105D	1 person office	151
	111B	2 person office	162
	111E	Visitor office/conference room	162
Natural Sciences	173	1 person office	151

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)
- Veeco interferometric microscope with sampling/strobing capability. This microscope is designed for measuring long-stroke motion of MEMS actuators to

very high accuracy (<1 nm) with microsecond time resolution. It is the newest instrument in our suite, delivered in January, 2007.

- 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

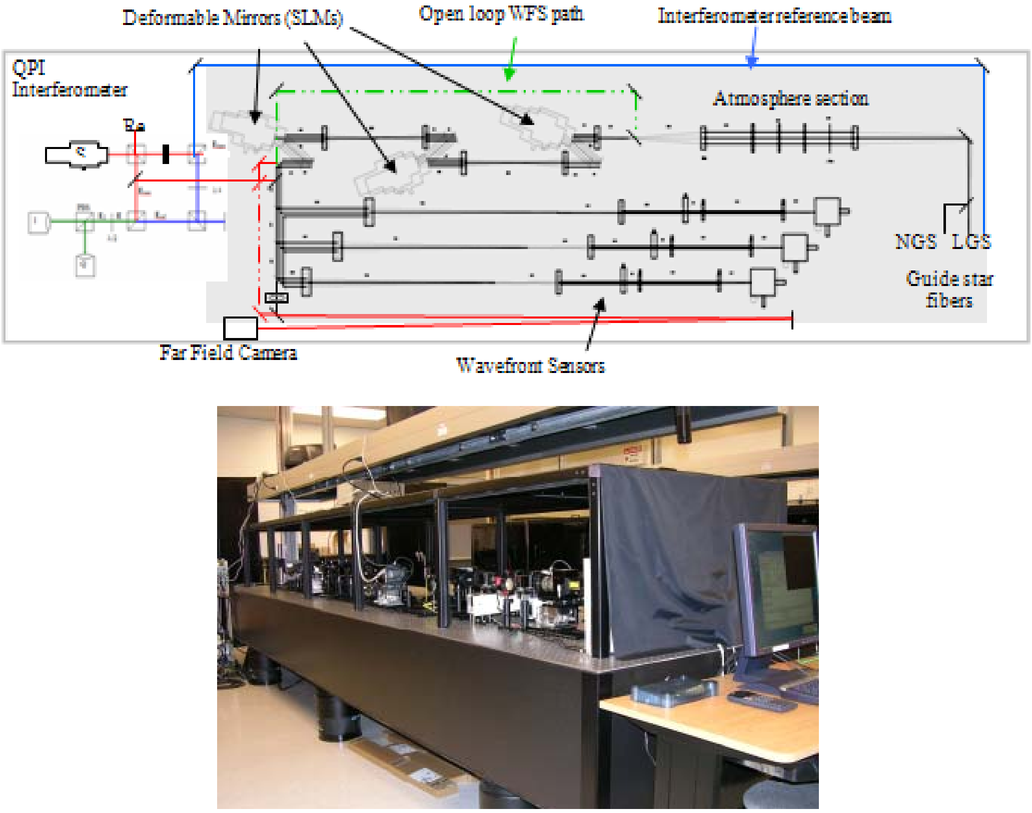

Figure 1. MCAO/MOAO Testbed showing major element and highlighting its reconfigurability for multiple guidestar wavefront sensors, closed loop (MCAO), and open loop (MOAO) architectures

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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.

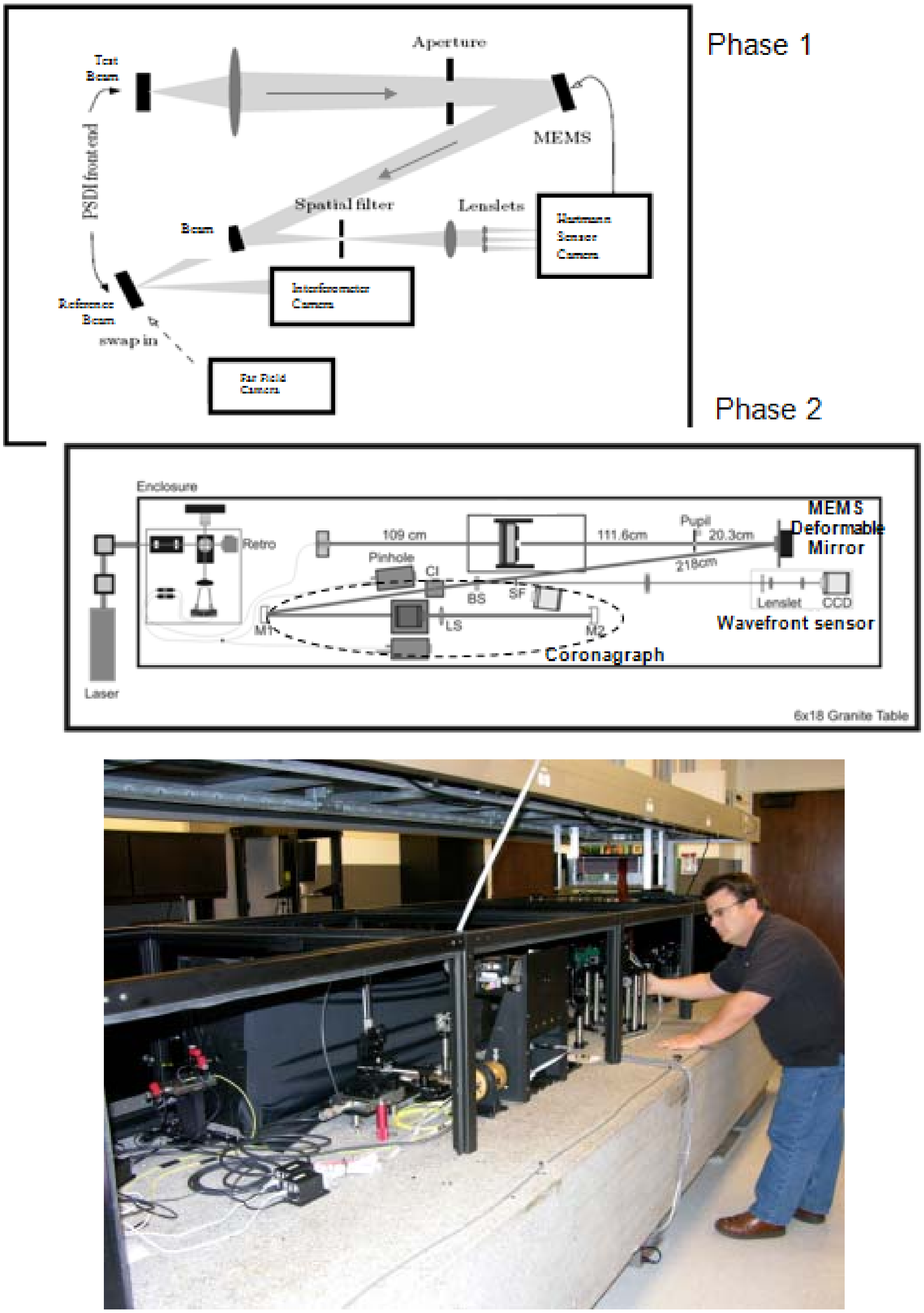


Figure 2. ExAO testbed progress from MEMS testing interferometer (Phase 1) to planet imager instrument prototype with diffraction-suppressing coronagraph (Phase 2).

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]. 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: The prototype extreme adaptive optics system continues to make progress verifying concepts and establishing performance standards for the Gemini Planet Imager. We have recently added coronagraph optics for direct measurement of the far-field contrast simultaneous with closed loop AO control.

Phase Shifting Diffraction Interferometer repeatability and stability

Early on, we tested the long-term stability of PSDI looking at both a reference flat mirror and MEMS devices. We obtain very repeatable and long-term stable measurements of wavefront and published results of these tests in 2004 and 2005[2,3].

The coronagraph upgrade added a number of elements into the optical path so we repeated the stability tests to assure that the resulting system was not degraded in accuracy. These tests have shown that the phase 2 system configuration is showing accuracy and stability properties similar to the previous setup, only slightly degraded due to the extra optics in the path. For example, where PSDI at focus #1 measured 0.68 nm rms, PSDI at focus #2 measured 0.92 nm rms. This is acceptable performance for continuing with our high-contrast coronagraph tests.

MEMS device characterization

We completed the two-year development contract with Boston Micromachines Corporation to provide 1000-element MEMS deformable mirrors in 2005. 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. Results of this work were published in 2006[4].

Wavefront control experiments

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

1) Flatten the MEMS surface to high accuracy
2) Measure an aberrated wavefront interferometrically and control the MEMS to flatten the wavefront to high accuracy
3) Measure the aberrated wavefront using a Hartmann sensor and control the MEMS to flatten the wavefront to high accuracy
4) With a coronagraph, measure the far-field corrected image to determine contrast possible with the flattened MEMS
5) With a coronagraph, measure the far-field corrected image after correction of an atmospheric aberration by the MEMS

So far, we are approaching but have not yet achieved one of the earlier stated goals for the ExAO testbed: a 1 nm rms total wavefront error after correction of atmospheric turbulence. Ongoing work is continuing to uncover additional sources of small error and we have achieved approximately 2 nm rms closed loop accuracy.[5,6] However since in a real observation the atmospheric error averages out quickly over time, the residual halo of light from uncorrected atmosphere only produces a smooth background that can be very accurately subtracted to reveal the point-source planet within it. We’ve found that a much more important issue is the residual wavefront error due to slow systematically varying aberrations within the instrument itself. These kinds of errors produce consistent speckles, which appear in the final image to look like planets. Therefore we have redirected much of our attention to the precision control of the mid spatial frequency phase and amplitude variations and to thoroughly understanding the sources of these variations which will ultimately contribute to loss of contrast at the focal plane in long exposure images. In the past year we developed a comprehensive wave-optic simulation code that predicts performance both in the ExAO testbed and in the GPI instrument and allows us to investigate potential troubles at the 10^{-7} contrast level.

Coronagraph contrast measurements

In 2005 we reported how, using a specially shaped pupil mask designed to suppress diffraction, we could control the MEMS to produce a far field image with a small wedge-shaped area that has better than 10^{-7} contrast. With the addition of the coronagraph upgrade in phase 2 we are now in a position to demonstrate a dark discovery region that surrounds the star, allowing more efficient detection anywhere around the star where we expect planets to be. A traditional hard-edge Lyot type coronagraph was inserted last year as a precursor to a more sophisticated design planned for this year. This allowed us to align and calibrate the phase 2 upgrade.

In June 2007 we received a specially designed pupil apodizer and corresponding gradient focal plane stop to build up within the testbed a prototype apodized-Lyot-coronagraph of the type that will be used in GPI (Figures 4 and 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. The difficulty is in manufacturing an optic that can smoothly vary transmission while not affecting phase. Devices from MEMS Optical, Inc. designed and specified by our GPI collaborators at the American Museum of Natural History are now undergoing testing on the ExAO testbed.

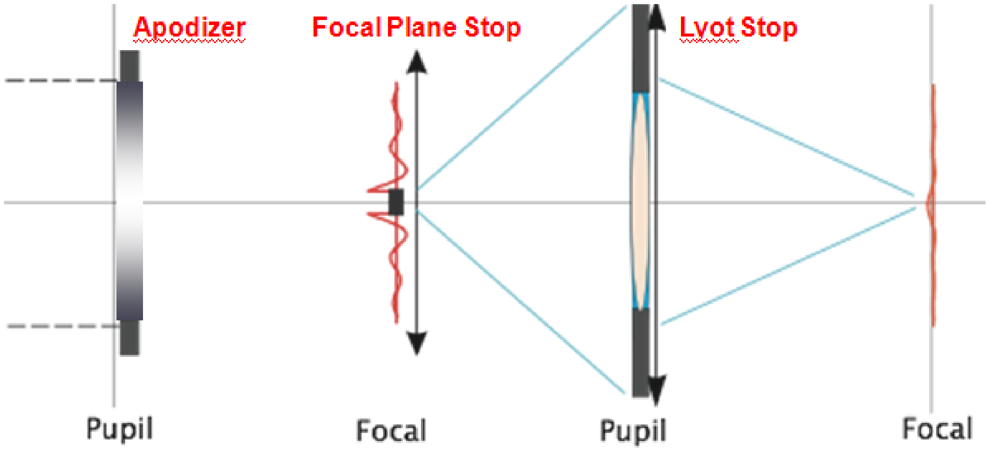


Figure 4. Layout of the apodized Lyot coronagraph.

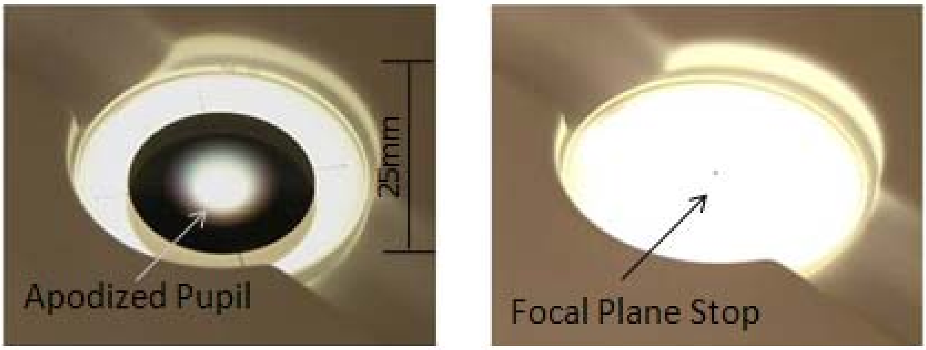


Figure 5. Photographs of the coronagraph apodized pupil (left) and focal plane (right) stops. Smooth gradation in transmission achieved through a microarray of 1 micron sized dots that vary in density across the optic. The size of these pieces is approximately 1 inch diameter.

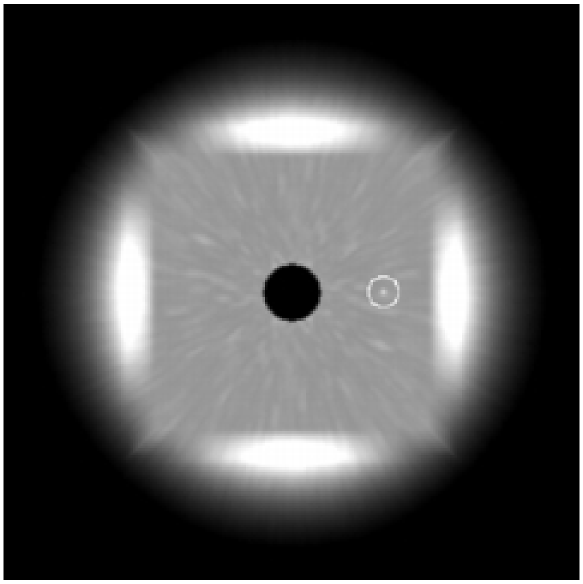


Figure 6. Simulation of the ExAO planet image using the GPI Coronagraph instrument. Wavefront control by the deformable mirror and diffraction suppression by the apodizing Lyot coronagraph carve out a dark square planet discovery region around the central star. Light from the central star is blocked by the coronagraph focal plane stop. The image is multi-wavelength so the small remaining diffraction patterns blur out into a uniform background leaving only streaked speckles due to imperfections in the optics and wavefront sensor calibration, as allowed in the GPI instrument error budget. The faint detected planet, a 1-million year old "warm Jupiter" still glowing under its own heat of formation, is shown circled in white on the right.

Experiment Results: 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 a 30-m telescope, one must scale 60 km of turbulent atmosphere and a 30-meter diameter telescope to fit on a room-size optical bench, while still retaining the proper diffractive behavior of the optical system. This scaling consideration has driven the optical design and layout of the testbed.

Optical path – MCAO mode

The MCAO optical testbed layout is shown in Figure 1. Light enters the system via laser fibers which emulate the guide stars, labeled NGS (natural guide star) and LGS (laser guide star) at the lower right of the figure. Here there is an array of sources to simulate a multi-guidestar constellation, plus one deployable source to simulate science objects at arbitrary locations in the field. The guide star and science object light travels through a series of phase aberration plates in the atmosphere section, to emulate multiple layers of air turbulence at different altitudes in the atmosphere. At this point the light is focused, as it would be in an actual telescope, then fed to a series of deformable mirrors (we are using liquid crystal spatial light modulators to perform the function of deformable mirrors). From there, the AO corrected light is sent to a number of Hartmann wavefront sensors, each of which senses an individual guide star. The AO corrected light also travels to a far-field imaging camera to characterize Strehl ratio and other performance metrics of the corrected imaging.

Another path goes to an interferometer to characterize AO-corrected wavefront quality. This interferometer records interferograms at high speed. The MCAO control system is designed to run at a quick pace 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.

MOAO mode results. Graduate student Mark Ammons (Astronomy, UC Santa Cruz) led the effort to prove the feasibility of multiple guidestar tomography to the accuracy needed for large telescope AO systems by performing experiments on the MCAO testbed. He used the MOAO mode of operation, that is, open loop measurement of wavefronts from multiple directions through the atmosphere combined to model the 3-D atmosphere and compute the correction needed for an arbitrary science direction. First results were presented at the 2006 SPIE meeting[7] and the latest results, which mock up the exact system we are considering for Keck Next Generation Adaptive Optics, were presented at the 2007 SPIE meeting[8]. This later experiment involved 5 laser guidestars on a 2 arcminute field and 4 science directions. The results are summarized in Figure 7.

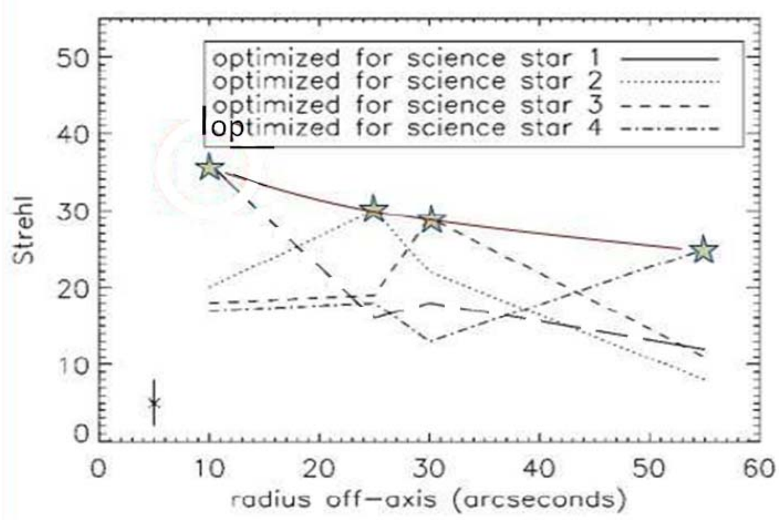
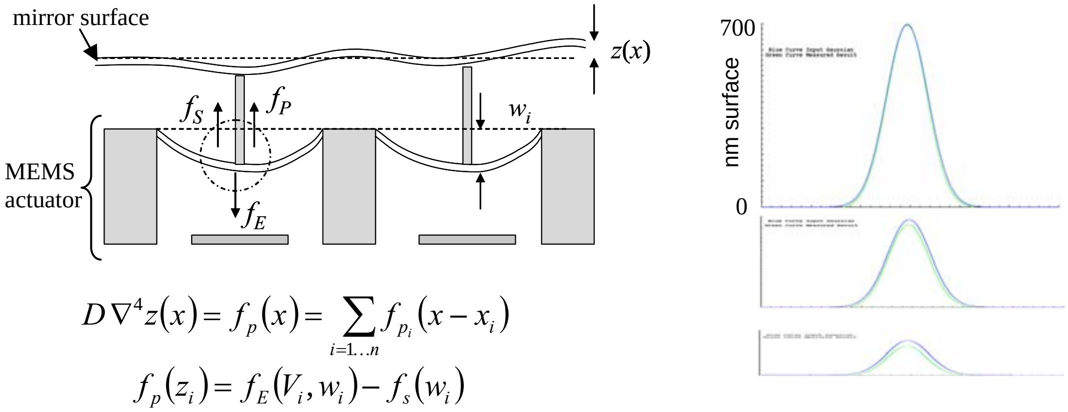


Figure 7. Strehl vs field angle on the wide-field MOAO experiment. Points on the solid line show the MOAO results obtained with tomographic sensing and projection onto deformable mirrors that are optimal for each of four science field directions. Dashed lines show the degradation of Strehl due to anisoplanatism, which ordinarily reduces the corrected field of view in present day single-DM systems. The widening of the corrected field due to tomography has been clearly demonstrated on the LAO testbed, and these experiments have also quantitatively validated the theoretical models.

MCAO mode results. 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. Unlike open-loop systems, closed loop systems can exhibit noise-driven instability. Long-term stability of MCAO has been an unknown because the complexity of a large aperture system has made computer simulations of more than a few milliseconds of real time impractical. Our experiments are showing the stability of closed loop controllers based on state feedback of conditional mean estimates[9]. A paper describing these results is now in preparation for journal submittal.

Component characterization. The MOAO system runs in “open loop,” that is, the effects of AO commands to deformable mirrors are not sensed by the wavefront sensors. This puts additional demands on the deformable mirror to respond accurately to commands without having to be re-measured. In experiments on a dedicated MEMS test station in the MCAO lab, we have developed an open loop deformable response model based on the basic principles governing thin plates and electrostatic actuators. This model is used to predict the actuator voltages necessary to move the mirror surface to a precise given wavefront shape. This year we demonstrated repeatable, one-step go-to correction to better than 30 nanometers peak-to-valley wavefront accuracy on the 32x32 MEMS devices and results were presented at the Photonics West conference in January[10]. This open-loop accuracy meets the specifications for infrared MOAO instrument error budget goals on both the proposed IRMOS instrument for the Thirty Meter Telescope and a similar multi-object integral field spectrograph for the Keck Telescope Next Generation Adaptive Optics system.



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

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

Figure 8 MEMS open loop modeling. Left: The mirror response is modeled as a combination of thin plate force, electrostatic force, and spring return force of the actuator. A series of tests assuming the thin plate equation governs the relation between plate deflection and plate forces can be used to resolve each of the three force components separately. These are stored in a lookup table and used to drive the mirror to prespecified shapes in open loop. Right: Laboratory test results with the 32x32 Boston Micromachines MEMS showing the difference between modeled and actual surface shape is within 15 nm peak-to-valley (30 nm wavefront).

Some of the components used in the MCAO/MOAO testbed are new technology and needed to be tested and characterized. In particular we spent some time calibrating the spatial light modulators so that they would work in open loop in MOAO configuration. The deformable mirrors (DMs) required for a 30-meter telescope AO system need many more actuators than are available on currently available DMs. Therefore we opted to use a liquid crystal spatial light modulator (SLM) manufactured by Hamamatsu Corporation as a surrogate deformable in our laboratory experiments. This device controls the optical phase with 768 x 768 pixel resolution and thus can easily emulate the 10,000 actuator deformable mirrors that would be needed on a 30-meter telescope. The Hamamatsu SLMs only work with polarized, monochromatic light, and thus are unsuitable for astronomy, but are completely adequate for laboratory testing of AO wavefront control. Our open-loop calibration of these devices is accurate to roughly 20 nm peak-to-valley wavefront and this has been the basis of successful tomographic MOAO experiments this year by graduate student Mark Ammons.

Hartmann wavefront sensors. Astronomy graduate student Mark Ammons has perfected procedures for aligning and calibrating Hartmann wavefront sensors to the accuracies that would be needed for open-loop measurement of wavefronts in large telescope MOAO systems. He presented results at two conferences this year[8,11]. The wavefront sensor optics and resulting Hartmann patterns from the MCAO testbed are shown in Figure 8.

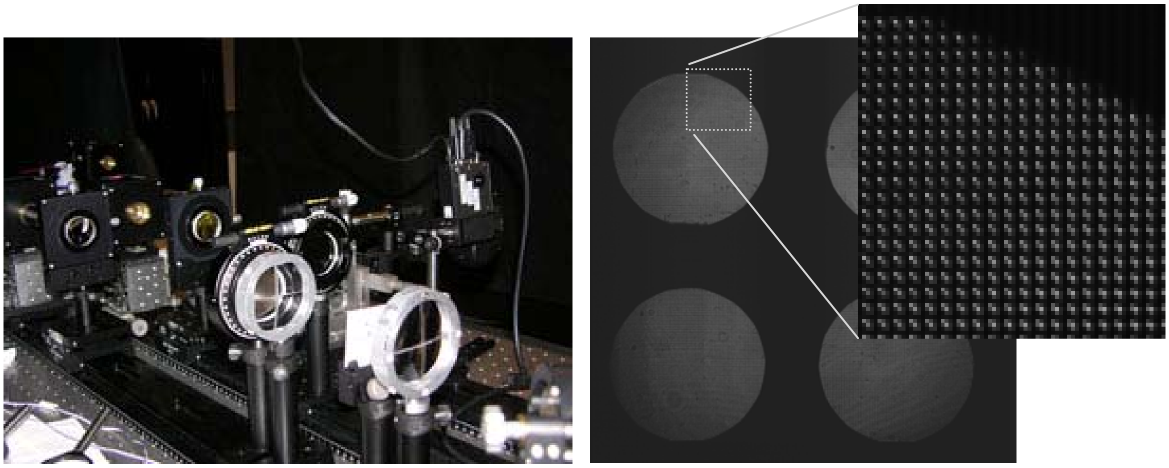
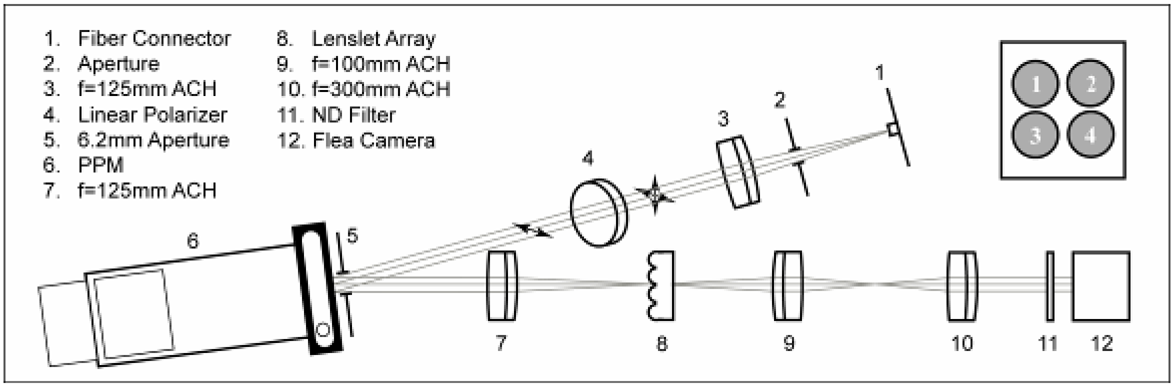


Figure 9. Left: photo of the multiplex wavefront sensor optics. Right, Hartmann patterns from multiple guidestars, showing patterns from 4 laser guidestars. The patterns have approximately 100 Hartmann spots across the aperture, protyping the TMT 10,000 degree of freedom AO system. The inset on the upper right shows details of the Hartmann spots, each a small image of the guidestar as derived from a small section of the overall telescope aperture.

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. We worked with a micro optic manufacturer, Vitrum Technologies, to produce a lenslet array to our specifications and tested it in a wavefront sensor arrangement in our laboratory. We have now completed measurements of the system performance with test aberration wavefronts generated by one of the spatial light modulators (Figure 10). Astronomy graduate student Jess Johnson is performing the experiments and initial results were reported at the 2006 SPIE telescopes conference [13].



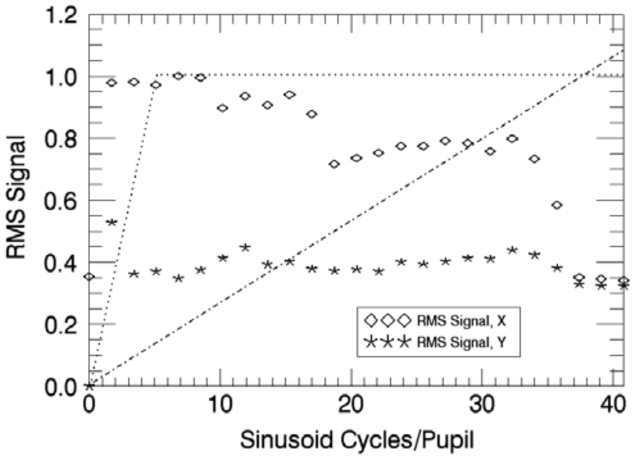


Figure 10. Pyramid lenslet wavefront sensor and experimental results. The response to phase aberration spatial frequencies is shown at the left, which is the first laboratory verification that the sensor acts to directly sense wavefront phase (uniform frequency response) as opposed to wavefront slope (linearly increasing with frequency). Furthermore the tests show the Nyquist cut-off (here at about 36 cycles/pupil) and an amplitude dependent nonlinearity of the sensor at 18 cycles/pupil, ascribed to second order diffraction.

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[14].

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[15]. 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.

Last year we had planned to test the massively parallel prototype system in closed loop on the MCAO testbed. However, faced with the high cost of implementing a full system of hardware or building a less than satisfactory low-order mock-up, we have decided to change emphasis this year. Commercially available FPGA simulators are mature enough today to reliably test the design concept without having to buy all the hardware. We will be using those to continue our effort, feeding it data input from our own atmospheric simulator or data from the MCAO testbed's Hartmann sensor measurements.

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. 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. (Now in final design phase, TMT has contracted with an outside firm for the detailed design.)

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 is now in final integration and test phase, with assembly and tests taking place in the LAO cleanroom facility (Figure 11).

Figure 11. Lab engineer Daren Dillon and graduate student Mark Ammons perform final alignments on the Villages instrument in the LAO. Hartmann sensor readout is shown on the display behind them.

Phase 1 of Villages will demonstrate MEMS based adaptive optics correction at visible to short infrared wavelengths (0.5 to 1.0 microns) in both the closed and open loop control configurations. This will demonstrate the fundamental components and methods needed for an MOAO system on a large telescope.

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

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

The configuration of the experimental instrument is shown in Figure 12. The system will be mounted at the Cassegrain focus (behind the primary mirror) of the Nickel 40-inch telescope. Light coming from the telescope on its way to the science camera reflects off of the MEMS deformable mirror, which applies the wavefront correction. The system is configured with two paths for starlight to enter into a Hartmann wavefront sensor of a multiplex design similar to those on the MCAO testbed. One path probes the wavefront prior to correction and other one after correction by the deformable mirror. This architecture enables either the closed or open loop operation and in each case provides diagnostic information about system performance by measuring both pre and post correction wavefronts simultaneously.

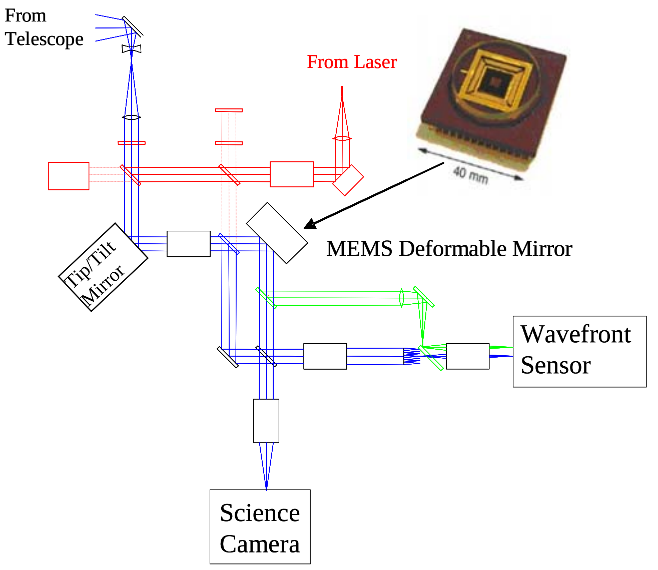


Figure 12. MEMS-AO / Villages system. The system employs a 140 actuator MEMS deformable mirror and fits on the back of the Lick Observatory 40-inch Nickel telescope.

The Phase 1 system has been assembled and is undergoing final integration and test within the LAO now. First light at the telescope is scheduled in September, 2007.

The as yet unfunded Phase 2 of this project will involve projecting a sodium guidestar laser off the primary aperture of the 1-meter telescope (red lines in the figure). An adaptive optics pre-correction of the beam for atmospheric aberrations the laser will encounter on the way up will produce an extremely small spot in the sodium layer, approximately 10 times smaller in angular extent than current LGS spots. Basic signal to noise calculations for wavefront sensing indicate that a factor of 10 improvement in spot size will decrease the laser power requirements by a factor of 100.

This would have a dramatic effect on the requirements for guidestar lasers, significantly reducing their cost and risk, and could open the door to practical visible light laser guidestar systems.

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

Summary of Milestones Accomplished in 2007

In summary, we have accomplished the following major milestones in 2007:

1. Completed construction of the Villages instrument which is destined to go to the Lick 40-inch telescope for on-sky testing of MEMS
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]
3. Completed the assembly of phase 2 of the ExAO testbed and performed initial tests of a prototype Lyot coronagraph destined for the Gemini Planet Imager instrument
4. Published results on high contrast imaging with MEMS[5,6]
5. Published results on open-loop modeling and control of MEMS[10]

The Future of the Laboratory for Adaptive Optics

There is one more year on the original grant. Because of successes in finding outside funding, we have a funding stream in hand for an additional 9 months at the current operating rate and would like to discuss a no-cost extension of the original grant.

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

1. Villages on-sky experiments demonstrating MEMS and open-loop adaptive optics
2. MCAO experiments on the testbed extended to include a number of additional configurations under consideration for TMT and Keck NGAO
3. Continued development of the pyramid wavefront sensor, including testing on the sky with the Villages experiment.
4. Validation of the performance of the apodized Lyot coronagraph on the ExAO testbed
5. Diagnosis and analysis of beam intensity and reflectivity issues as they relate to high contrast imaging, using the ExAO testbed

The major programs we are pursuing are listed below:

- GPI commitment
- NSF MRI/ATI-funding of the laser program with Villages as the testbed
- Keck NGAO major role in component development/testing/construction

- Ever-larger role in TMT simulations, component development
- Major role in the TMT IRIS instrument. First-light IFU spectrometer to work behind AO

Our work has enabled a new wave of adaptive optics technologies which are now beginning to show tremendous 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 baselining 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 reasearcher, PhD in Astronomy and Masters degree in laser technology. Experimentalist and analytic modeler for MCAO and ExAO.

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

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

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

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

Julia Evans (guest, 1/4 time consultant) – UC Davis Graduate Student in Applied Physics, recently graduated and transitioning to postdoctoral researcher at LLNL. Performing experiments characterizing MEMS and high contrast imaging on the ExAO testbed.

Scott Severson (guest from UCO/Lick) – PhD Research Astronomer. Helping with ExAO experiments. Now has a faculty position at Sonoma State University

Mark Ammons (supported in part by a 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.

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

Eddie Laag – Graduate student researcher, UC Riverside Astronomy Department. Performing closed loop MCAO experiments on the MCAO testbed. Eddie recently returned to UC Riverside to complete his degree there after having successfully demonstrated stability of closed-loop tomography on the MCAO testbed.

Luke Johnson (supported by the Center for Adaptive Optics graduate fellowship) – Graduate Student in Electrical Engineering. Performaing experiments on the MCAO testbed experimenting with dynamic predictive control algorhithms.

Financial Report

This year LAO spent a total of $1,552,096, including outstanding liens of $144,340. When compared to this year's budget of $1,582,309, the overall result is a positive 2% variance of $30,213.

The variance in Personnel equaled $1,838 including the outstanding agreements for LLNL personnel or $140,309 excluding these agreements. Moreover, nearly $62,000 in salary and benefit savings occurred from the leverage of funds provided by NSF for the Visible Light

Instrument and by Keck Observatory for the Next Generation Adaptive Optics System Design Phase.

The most significant budget line item variances occurred in Projects with a negative 9% variance of $141,813, One-time Costs with a negative 5% variance of $84,779 and Operating Costs with a positive 2% variance of $29,967.

The variance in Projects was driven by the acquisition of three major pieces of equipment. Reallocating Director's discretionary funds, LAO procured a CCD System for $41,000, a Floralis deformable mirror for $32,000 and an interferometric microscope for $80,000. The latter we purchased in collaboration with Engineering Professor Joel Kubby. LAO funded 65% of the microscope and it will remain in the LAO facility. In the category of One-time Costs, we spent about $38,000 on new furniture and $31,000 in minor renovations on the new space described in Facilities.

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