Progress with Adaptive Optics Testbeds at the UCO/Lick Observatory Laboratory for Adaptive Optics

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ABSTRACT

We report on experimental results with adaptive optics testbeds at the UCO/Lick Observatory. One testbed is dedicated to high contrast AO imaging and is a prototype for a ground-based extrasolar planet imager for the Gemini telescope. The second testbed is dedicated to developing concepts and architectures for multi-laser guidestar tomography in wide-field AO applications. Such systems are now under consideration for the Keck and Thirty Meter Telescope. Concurrent with the testbed experiments we are evaluating new components and key technologies applicable to the next generation of AO systems including MEMS deformable mirrors, high speed low noise detectors, wavefront sensing methods, and fast wavefront control processors.

1. INTRODUCTION

The Laboratory for Adaptive Optics (LAO) was founded as part of the UCO/Lick Observatory in 2002 with a start-up grant from the Gordon and Betty Moore Foundation. The Laboratory has with three main instrumentation research areas: Multiconjugate Adaptive Optics (MCAO), Extreme Adaptive Optics (ExAO), and next generation AO component development. 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.

The 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.

One of the first instruments to begin operation in the lab is the Phase-Shifting Diffraction Interferometer (PSDI) with the ability to measure absolute wavefronts to 0.1 nanometer accuracy. The PSDI was used in the initial characterization of micro-electromechanical systems (MEMS) deformable mirrors as we began to work with vendors to construct prototypes suitable for astronomy application. The PSDI was later modified to a Phase 2 version, with a second pupil and the ability to characterize the performance of ultra-high contrast coronagraph designs.

A second optical table is dedicated to an MCAO testbed which is designed to emulate a layered turbulent atmosphere and a complete multi-guidestar tomography system for a 30 meter telescope.

Several additional optical bench areas are dedicated to a number of component development efforts. We have ongoing experiments with pyramid wavefront sensors, MEMS open loop control, woofer-tweeter DM control, and high-speed parallel processors for MCAO tomography reconstruction.

2. EXTREME ADAPTIVE OPTICS (PLANET IMAGING) TESTBED

The ExAO program, with its ambitious goal of directly imaging of extrasolar planets from the ground, 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.

The Phase-Shifting Diffraction Interferometer (PSDI) can measure absolute wavefronts to less than 0.5 nm rms accuracy with long term stability and repeatability.[2] After setting up the PSDI, a Boston Micromachines Corporation (BMC)1000 element continuous face sheet MEMS deformable mirror was flattened to less than 1 nm rms and generated a high contrast ($<10^{-6}$) far-field image.[3-7] This flatness has been routinely achieved with a number of 32x32 MEMS mirrors we now have in-house as a result of a development contract with BMC.

Then ExAO testbed/prototype instrument has continued to be modified. In 2005 we added a Hartmann sensor and began the process of calibrating it using the PSDI as the truth reference. 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. We implemented an anti-aliasing spatial filter at the Shack-Hartmann wavefront sensor in order to reduce the dependence of Hartmann spot size on the seeing conditions. This has worked out well, following the theory presented by Bruce Macintosh and Lisa Poyneer.[8]

We recently added a second stage of the testbed with two spherical mirrors forming a second pupil and focal plane. The spheres have very low mid-spatial frequency surface error and are prototypical for the high quality optics required in the planet imager instrument. The second stage permits testing coronagraph optics in cascade with closed loop AO control utilizing PSDI's high precision. We began with validating the performance of a classic hard-edged Lyot coronagraph and now are testing new designs of an apodized-pupil Lyot coronagraph design being developed in collaboration with Remi Soummer at the American Museum of Natural History.[9]

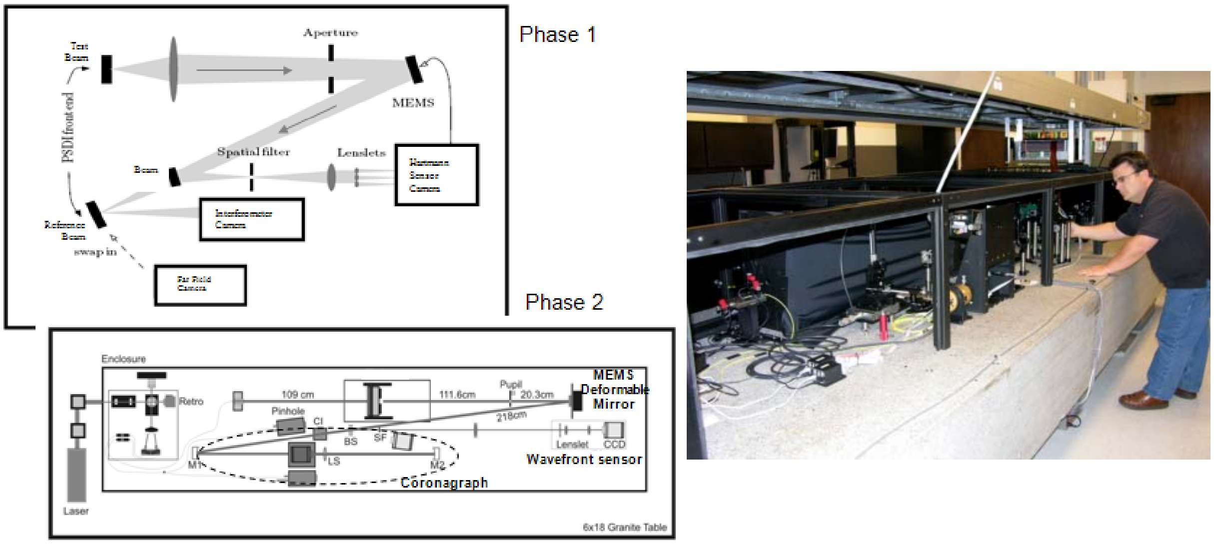

Figure 1. ExAO testbed progress from MEMS testing interferometer (Phase 1) to planet imager instrument prototype with diffraction-suppressing coronagraph (Phase 2).

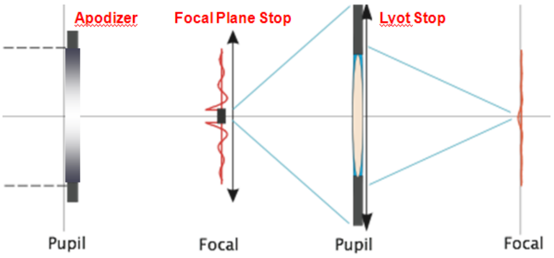

Figure 2. Layout of the apodized Lyot coronagraph. (Drawing courtesy Remi Soummer, American Museum of Natural History)

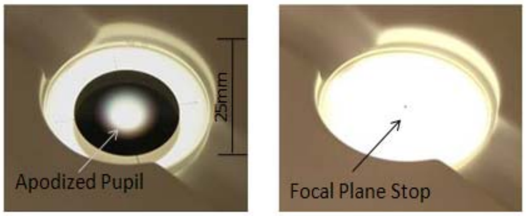

Figure 3. Photographs of the coronagraph apodized pupil (left) and focal plane (right) stops. Smooth gradation in transmission achieved through a microarray of small dots that vary in density across the optic. The size of these pieces is approximately 25mm diameter.

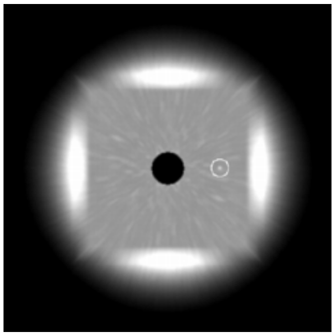

Figure 4. Simulation of the ExAO planet image using the GPI Coronagraph instrument. Wavefront control by the deformable mirror and diffraction suppression by the apodizing Lyot coronagraph carve out a dark square planet discovery region around the central star. Light from the central star is blocked 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.

3. MULTI-CONJUGATE ADAPTIVE OPTICS TESTBED

The multi-conjugate adaptive optics (MCAO) testbed is intended to test new concepts and technologies for the next generation of high Strehl AO systems on large telescopes. A bird's eye view layout of the MCAO testbed is shown in Figure 5.

The testbed can be arranged in closed loop or open loop configuration. The closed loop configuration has a series of deformable mirror positions, each at a conjugate to specific altitudes in the atmosphere, followed by multiple wavefront sensors. The open-loop configuration senses the wavefront before it reflects off the deformable mirrors, a configuration under consideration for multi-arm spectrograph AO systems.[10]

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.

The MCAO optical testbed layout is shown in Figure 7. 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.

MOAO experiments. The MCAO arrangement on the optical bench can be conveniently switched to an MOAO configuration (the green dotted line path in Figure 7). 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.

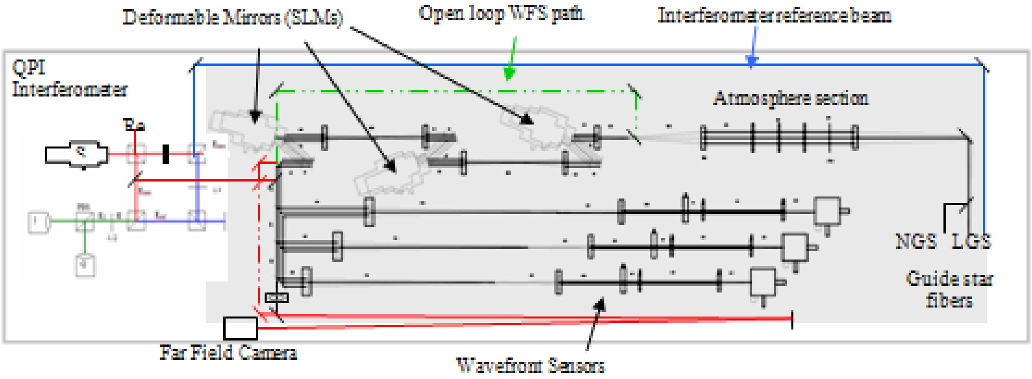

Figure 5. MCAO/MOAO Testbed showing major element and highlighting its reconfigurability for multiple guidestar wavefront sensors, closed loop (MCAO), and open loop (MOAO) architectures

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MOAO mode results. Graduate student Mark Ammons (Astronomy, UC Santa Cruz) led the effort to prove the feasibility of multiple guidestar tomography achieving 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[11] 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[12]. This later experiment involved 5 laser guidestars on a 2 arcminute field and 4 science directions. Some of the results are summarized in Figure 6.

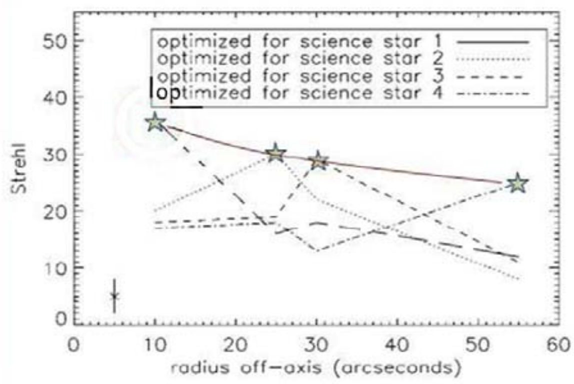
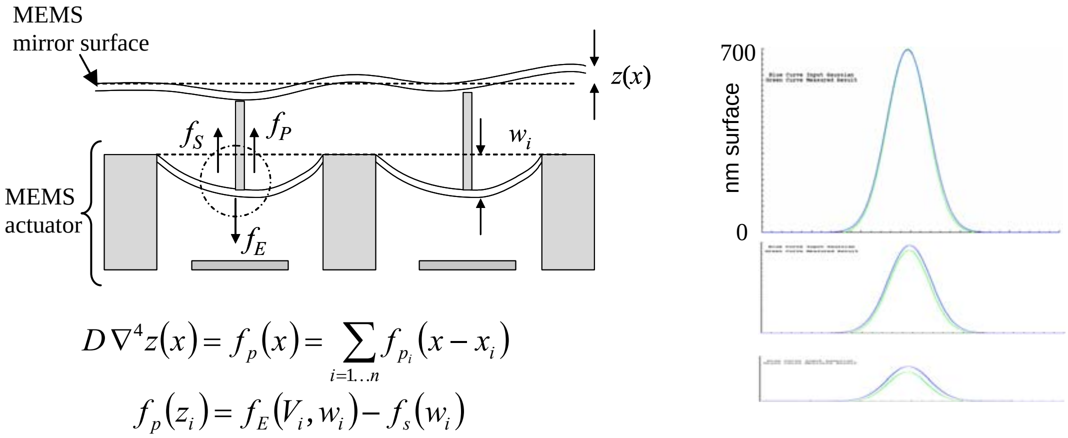


Figure 6. Strehl vs field angle on the wide-field MOAO experiment. Points on the solid line show the MOAO results obtained with tomographic sensing and projection onto deformable mirrors that are optimal for each of four science field directions. Dashed lines show the degradation of Strehl due to anisoplanatism, 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[13]. A paper describing these results is now in preparation for journal submittal.

4. COMPONENT DEVELOPMENT

MEMs Deformable Mirrors. 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. Results were presented at the Photonics West conference in January by astronomy graduate student Kate Morzinski[14]. 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 7 MEMS open loop modeling. Left: The mirror response is modeled as a combination of thin plate force, electrostatic force, and spring return force of the actuator. A series of tests assuming the thin plate equation governs the relation between plate deflection and plate forces can be used to resolve each of the three force components separately. These are stored in a lookup table and used to drive the mirror to prespecified shapes in open loop. Right: Laboratory test results with the 32x32 Boston Micromachines MEMS showing the difference between modeled and actual surface shape is within 15 nm peak-to-valley (30 nm wavefront).

Hartmann wavefront sensors open loop calibration. Astronomy graduate student Mark Ammons has been developing procedures for aligning and calibrating Hartmann wavefront sensors to the accuracies that would be needed for open-loop measurements in large telescope MOAO systems. His presentations on MOAO[11,12] describe the results of this effort. The wavefront sensor optics and resulting Hartmann patterns from the MCAO testbed are shown in Figure 8.

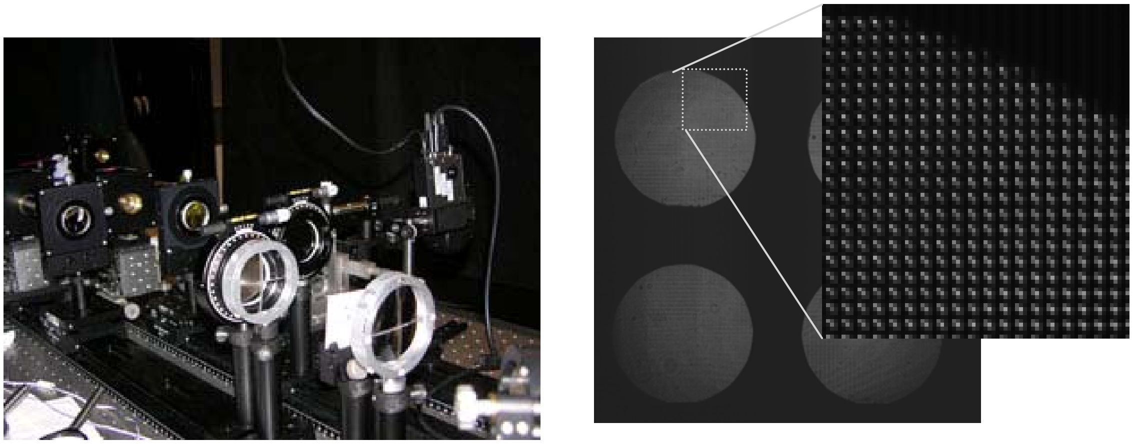


Figure 8. Left: photo of the multiplex wavefront sensor optics. Right, Hartmann patterns from multiple guidestars, showing patterns from 4 laser guidestars. The patterns have approximately 100 Hartmann spots across the aperture, protyping the TMT 10,000 degree of freedom AO system. The inset on the upper 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 an efficient implementation of the pyramid wavefront sensor using precisely fabricated micro-lenslet arrays as the combination quad knife edge plus pupil re-imager lens.[16] The pyramid sensor is more light-efficient alternative to the Hartmann wavefront sensor because of its ability to act in an interferometric mode as a direct phase sensor. The micro-optic lenslet array splits the light at the focal plane into four quadrants which are each detected at subsequent pupil images. The resulting interference fringe patterns in each of the four pupil images contains the wavefront phase information.

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 pyramid wavefront sensor arrangement. Initial performance measurements were reported at the 2006 SPIE telescopes conference by astronomy graduate student Jess Johnson.[13]

Real-time tomography hardware. The tomography algorithms needed to command multiple deformable mirrors given measurements from multiple laser guide stars are quite computationally complex, and require an extraordinary amount of computing power to be able to implement them in real time for large telescope AO systems. Prior work in this area has shown that the minimum-variance control algorithm for laser guidestar MCAO has a structure that is similar to the back-projection algorithms used in medical tomography[18]. These algorithms have a repeated structure that is amenable to massive parallelization of the computations. Therefore we subsequently pursued the development of massively parallel tomographic compute architectures for the real time MCAO and MOAO control algorithms[19]. 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.

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. A similar massive-parallelization concept has been adopted as the baseline for the TMT AO design.[20]

5. ON-SKY EXPERIMENTS: MEMS AO / VIILLAGES

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 2006 we began to design an experimental instrument to take to the Nickel 40-inch telescope at Mount Hamilton. The system, designated as Villages – Visible Light Laser Guidestar Experiments, is now in final integration and test phase, with assembly and tests taking place in the LAO cleanroom (Figure 9).

Figure 9. 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 a MEMS-based 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 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 10. The system will be mounted at the Cassegrain focus (behind the primary mirror) of the Nickel 40-inch telescope. Light coming from the telescope on its way to the science camera reflects off of the MEMS deformable mirror, which applies the wavefront correction. The system is configured with two paths for starlight to enter into a Hartmann wavefront sensor of a multiplex design similar to those on the MCAO testbed. One path probes the wavefront prior to correction and other one after correction by the deformable mirror. This architecture enables either the closed or open loop operation and in each case provides diagnostic information about system performance by measuring both pre and post correction wavefronts simultaneously.

The 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 Ocotber, 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

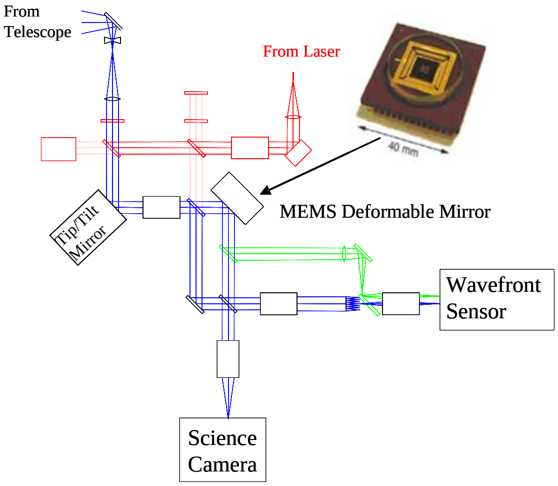


Figure 10. MEMS-AO / Villages system. The system employs a 140 actuator MEMS deformable mirror and fits on the back of the Lick Observatory 40-inch Nickel telescope.

small spot in the sodium layer, approximately 10 times smaller in angular extent than current LGS spots. Basic signal to noise considerations 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.

6. THE FUTURE OF ADAPTIVE OPTICS

A new wave of adaptive optics technologies is coming of age: micro deformable mirrors, very efficient wavefront sensors, and massively parallel computation for complex multi guidestar wavefront sensing. A combination of these technologies could potentially dramatically reduce the laser power needed for visible light LGS AO systems if they are combined with laser uplink AO correction. These advances will have a profound impact on visible instrumentation, and the ensuing science to be had from it. We foresee covering the complete visible wavelength spectrum with diffraction-limited imaging and spectroscopy, and giving access to the whole sky with laser guidestars. This would revolutionize visible light astronomy as well as significantly reduce the size and costs of instruments.

A reasonable metric of science productivity for astronomical telescopes is the signal-to-noise per unit exposure time. With adaptive optics, this metric scales as telescope diameter to the fourth power, as compared to telescope diameter squared without AO, so science output is vastly improved by equipping new instruments on the large telescopes with adaptive optics at every wavelength band it is effective.

The Laboratory for Adaptive Optics will continue to pursue these new avenues of development and will continue to foster new ideas and experimentation.

7. ACKNOWLEDGEMENTS

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