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MEMS-AO / VILLAGES

MEMS in Astronomical Adaptive Optics
Visible Light Laser Guidestar Experiments

On-sky Experiments at the Nickel 40inch Telescope to Demonstrate Next Generation Adaptive Optics Concepts for Extremely Large Telescopes

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1 Introduction and Background

The Lick Observatory has been a pioneer in the development of innovative technology for astronomy particularly the development of adaptive optics and laser guidestar systems. Adaptive optics enables high resolution observing with from the ground by actively correcting for the distorting effects of the turbulent atmosphere above the telescope. The laser guidestar adaptive optics system installed at the Lick 3-meter Shane Telescope in 1996, was the first such system to be commissioned for regular observing in astronomy. Subsequently a laser guide star system of this same design was installed at the Keck 10 meter telescope and is presently producing ground breaking results in extragalactic science, solar system science, and science of the center of our Galaxy.

Building on this earlier success, the next generation of telescopes and adaptive systems will want to realize the full potential of high Strehl, wide field / multiplex observing. A number of efforts have begun along these lines including feasibility studies for a Thirty Meter Telescope and for next generation adaptive optics system on the Keck ten-meter telescope. On the TMT, all infrared instruments and a few of the visible wavelength instruments are being designed to utilize adaptive optics. Near infrared science instruments will employ multiple laser beacons to provide tomographic measurement of the volume of atmosphere above the telescope. On Keck, the next generation high precision AO system will utilize multi-guidestar tomography for science observing down into the visible wavelength bands.

The UCO/Lick Observatory Laboratory for Adaptive Optics (LAO) is actively pursuing development of new device technologies and techniques that will enable the next generation of adaptive optics systems for astronomy. Experiments at the LAO have demonstrated the multi-guidestar tomography and wide-field wavefront correction techniques. In addition, the LAO has been developing, in coordination with industry, new device technologies for wavefront sensing and control.

We propose to field an on-sky experiment that will demonstrate two new key technologies for next generation adaptive optics on large telescopes. These key technologies are: MEMS electrostatically-actuated deformable mirrors and pulsed lasers for efficient generation of laser guidestars with a minimum of laser power.

2 Proposed Experiments

2.1 MEMS Open Loop Experiment

A particularly important new development for adaptive optics is a radically different kind of adaptive mirror technology which has been successfully tested in our laboratory over the past year. The mirror is fabricated using silicon micro-machining technology to create a micro-electro-mechanical system (MEMS). The MEMS mirror and actuators are fabricated on a single chip of silicon in much the same way as a CCD or integrated circuit is fabricated. The silicon foundry approach enables devices with very high numbers of actuators at high reliability and low cost. We have tested a number of 1024 actuator MEMS deformable mirrors in our laboratory and are now embarking on a collaborative effort to develop a 4096 actuator device. Such mirrors will change the paradigm of how AO systems are designed and built. Their low size weight and cost will mean MEMS DMs can serve unique new roles not normally considered for active optics and which will drastically improve the performance of astronomical AO systems. These include, in addition to correcting the incoming starlight, correcting the wavefronts of laser beacons (both outgoing beam and return beams at the wavefront sensor), correcting the wavefronts of tip/tilt reference stars, and correcting science wavefronts at a multiplicity of field points.

MEMS actuators have very reliable and predictable response to applied command voltages. For this reason, it is practical to operate them “open-loop,” that is, without requiring that the guide star light be used to monitor the mirror’s surface shape. This opens up a powerful new architectural concept for AO called multi-object adaptive optics (MOAO) where several science objects can be observed simultaneously each using its own deformable mirror for correction. A recent study for the Keck next generation adaptive optics system has predicted that the multiplexing advantage of MOAO could provide a factor of 50 increase in science data collection rate – essentially the same as building 49 more Keck telescopes!

We propose to demonstrate the performance and reliability of MEMS deformable mirrors for astronomical instruments by building a MEMS based single-arm MOAO system and fielding it at the 40-inch telescope at Mount Hamilton. Such a system will make diffraction-limited images at visible wavelengths using bright natural stars as reference beacons and will clearly demonstrate two points: 1) the ability of MEMS DMs to perform as wavefront correctors for astronomical light and 2) MEMS unique ability to work accurately in open loop operation with real starlight and under typical atmospheric turbulence conditions.

2.2 Laser Projection Experiment

Another extremely important component technology for the next generation of adaptive optics is the laser that produces the guidestar. Laser-induced beacons provide the bright wavefront reference sources needed for probing the atmospheric aberrations anywhere the astronomer wishes to observe; bright enough natural guide stars being unavailable over most of the sky. Future generation AO systems will also require multiple laser guidestars in order to tomographically measure of the volume above the telescope.

Increasingly precise wavefront measurements, e.g. for correction at shorter wavelengths, require increasingly greater return signal. Recent advances in solid state laser technology, partially supported through the NSF sponsored Center for Adaptive Optics headquartered at UC Santa Cruz, have lead to the possibility of small power efficient sodium guidestar lasers. Although these lasers show promise, there is still considerable expense and uncertainty involved with scaling them to very high power.

In order to achieve the ambitions goal of laser guidestar adaptive optics correcting at visible science wavelengths, we have begun to investigate novel means of increasing the guide star signal without increasing the required laser power. Our suggested approach is, instead of increasing the laser power, to decrease the apparent beacon size. Wavefront measurement theory trades these off in a manner favoring the smaller spot: each factor of two improvement in spot diameter is equivalent to a factor of four increase in laser power.

A smaller spot is produced by pre-correcting the laser beam's phase wavefront for the atmospheric distortions it will see on the path up through the atmosphere and then projecting it out of a large aperture to produce a diffraction-limited beacon spot. Taking into consideration the thickness of the mesospheric sodium layer, the ideal projection aperture for a sodium guidestar laser is around 70 cm in diameter. In our proposed experiment, this condition is ideally met by using the 1-meter Nickel telescope as the laser projection aperture. An AO corrected laser beam projected through this aperture will produce a spot that appears 0.2 arcseconds in extent. Comparing with the roughly 2.0 arcsecond diameter spots of current LGS AO systems the resulting gain in signal to noise would be roughly a factor of 100, with no increase in laser power.

In order for us to verify that the spot is in fact that small, it must be imaged using an AO system that can resolve it. The MEMS based AO system described in section 2.1 will be used to do this in the following manner. First, the adaptive optics control loop will be closed using a bright natural guide star as a reference beacon. The wavefront control signal that is used to adaptively correct the incoming light can also be used to pre-correct the laser light for its path through the atmosphere. In our experiment the launch aperture and path through the atmosphere are shared between outgoing laser light and incoming starlight. The laser light must be pulsed, or chopped, so that incoming light can be sent to a detector in between outgoing laser pulses. The laser light is fed into the optical train of the telescope via a beam splitter (a polarizing beam splitter will allow most of the polarized laser light to be projected), and thus projected out the 1 meter aperture to the sodium layer. The projection angle will be slightly offset from the natural star so that the LGS spot appears separate but not too far separated from the natural star. Return light from the sodium layer, coming back after an approximately 600 microseconds round trip time, is gated into the detector. The focal plane detector will see both the natural star and the laser star, both corrected by the AO system to the diffraction limit of about 0.2 arcseconds full width half maximum. An image of the LGS spot that is close to this diffraction limit proves that the spot-sharpening concept is working.

As a final step in our proof of concept, the return laser beacon light can be sent into the wavefront sensor. We can then close the loop with the laser guide star. At first, the laser is not sharpened so the signal to noise is not sufficient for correcting at the frame rate necessary for visible AO correction, however, by starting at a lower frame rate and gradually increasing it, the control loop gradually increases its correction of the guide star and the beacon is sharpened by the AO system in bootstrap fashion. This "pulling oneself up by one’s bootstraps” method of starting a control loop is commonly done in practical control systems. A successfully closed AO loop at visible wavelength correction frame rates will prove our basic hypothesis: that visible wavelength laser guidestar AO is feasible with modest laser power.

3 Summary of Program Goals

The experiments we propose are in a series of 4 demonstrations, each producing their results in a timely manner and each demonstrating a key principle that stands alone as a milestone in the path to the next generation of AO systems. We believe that the experiments can be performed in a 2 year timeline, with experiments 1 and 2 (MEMS demonstration) happening in year 1 and experiments 3 and 4 (with the laser) happening in year 2. The start of year 2 will be contingent on availability of a suitable test laser for our use, an issue we will discuss in a subsequent section.

The experiments are summarized in Table 1.

Table 1. Summary of MEMS-AO / Villages Experiments

Phase	**Experiment Description**	**Demonstrates**	**Impact**
Phase 1			
Experiment 1	Closed loop on-sky demo using MEMS	MEMS will work for astronomical AO	Reduced risk for Keck and TMT AO
Experiment 2	Open loop on-sky demo using MEMS	MEMS will work in the MOAO architecture	MOAO architecture is feasible for Keck and TMT designs
Phase 2			
Experiment 3	Produce small LGS spot with Uplink AO	A small LGS spot can be produced; SNR increased	Choice of laser and launch facility for Keck, TMT
Experiment 4	Close the loop on the small spot LGS	Small LGS spot concept works	Visible λ AO system designs

The broader impact of these experiments is worth noting:

- A number of the precursor experiments have been performed in the Laboratory for Adaptive Optics, for example demonstration of the ability of the MEMS deformable mirror to correct for test aberrations similar to those of the atmosphere and demonstration of MEMS DM open loop performance. *The on-sky experiments are a natural next step in the flow of technology from laboratory to telescope instrument.*
- The Laboratory employs a number of graduate students and post doctoral researchers in astronomy and engineering. Hands on experience in the laboratory, followed by hands on experience at the telescope (the Nickel Telescope on Mt Hamilton is a two hour drive from the UC Santa Cruz campus) *inspires student involvement in instrument design and provides valuable observing experience. It also educates the next generation of adaptive optics instrumentalists.*
- These experiments demonstrate the resources of the UCO/Lick Observatory and the Laboratory for Adaptive Optics, *continuing a tradition of pioneering technology for astronomy.*

4 Exploratory High Risk Nature of the Proposed Research

The new concepts for adaptive optics systems outlined above have never been tried before on astronomical instruments. Nor are they on the main stream for future generation systems because of their high risk. A successful demonstration on a small telescope will give them high credibility which would result in a high impact on the future of AO instrumentation. The risks we face are:

- MEMS survivability and performance in the observatory operating environment
- Practical issues with laser uplink correction
- The process of closing the control loop while making the spot small

These risks are surmountable with good planning. However the entire concept is new and involves a series of techniques untried before in astronomy. The project plan calls for a progression of four experiments where success at any stage will have profound impact on the nature of future AO systems (as outlined in Table 1.)

5 Connection to the Large Telescope Projects

The principal investigator has had extensive experience in developing the first generation of laser guidestar adaptive optics systems, and was responsible for significant components of the Lick 3-meter and Keck 10-meter AO systems. He recently served as chair of the Thirty Meter Telescope adaptive optics working group and led the feasibility study for the IRMOS adaptive optics system. IRMOS uses the MOAO architectural concept and even though the science advisory committee ranked it highest priority among the infrared science instruments for TMT, it was put on hold by the project office pending demonstration of the MEMS technology it depends on. The PI is also involved with the Keck telescope next generation adaptive optics project which may also use the MOAO architecture pending demonstration of the key technological concepts.

6 Management, Schedule, and Budget

The schedule spans two years with experiments 1 and 2, involving proof of concept for the MEMS, happening in year 1 and experiments 3 and 4, involving tests with the laser, happening in year 2. At this time we are requesting for funding for the first year’s efforts, which include preparations for the laser experiments of year 2.

The project will be managed by the PI, who is director of the Laboratory for Adaptive Optics, and significant portions of the design and fabrication work will be performed by the UCO/Lick optical shops. Optics alignment, AO real-time software, integrated testing, and on-telescope experiments will be performed by LAO personnel. This work will be funded through a grant from the NSF Small Grants Exploratory Research program, leveraged with partial support from the LAO and from the Observatory operating budget.

Major component purchases are the MEMS deformable mirror and drive electronics from Boston Micromachines Corporation (with whom we have been partnering to produce MEMS DMs for astronomy), and a high speed wavefront sensor CCD and control electronics from SciMeasure Incorporated. Other components include optical lenses, mounts, a tip/tilt mirror, and optical breadboard. The real-time control computer will be a spare from the 3-meter AO system. The CCD science camera will be the existing camera that is used for science observing on the Nickel telescope.

Because of the truly urgent need to prove these concepts in time for making design decisions for TMT and Keck AO instruments, we plan to mount the system and get it operational on a very short time frame. The aim is to complete installation and begin observations before the winter rainy season, i.e. to start observing in the November 2006 time frame. This late autumn period is also the season with the best and most stable atmospheric seeing, which should provide us with ideal conditions for first light experiments in contrast to the rather turbulent and uncertain conditions in the early spring.

The total cost of the project is on the order of $500K. Detailed budget estimates will be available at the time of the preliminary design review.