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UCO/Lick Laboratory for Adaptive Optics – Developing Adaptive Optics Technology for the Next Generation of Astronomical Telescopes

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ABSTRACT

The Laboratory for Adaptive Optics is a newly founded component of the University of California Lick Observatory which is charged with the development of new technologies and methods for adaptive optics for ground based observatories. The Laboratory has two main experimental objectives: developing multi-laser guidestar tomography / multi-conjugate adaptive optics for wide-field imaging and developing high contrast "extreme" adaptive optics for imaging extrasolar planets. The laboratory is also evaluating the new components and key technologies needed for future AO systems including MEMS deformable mirrors, high speed low noise detectors, wavefront sensing methods, and fast wavefront control processors. The UCSC location provides a laboratory environment where students and postdocs will be trained in adaptive optics design, modeling, and implementation. This paper will give an overview of the status and future plans of the Laboratory.

1. INTRODUCTION: PURPOSE OF THE LABORATORY

The Laboratory for Adaptive Optics (LAO) has completed the third 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 those in space.

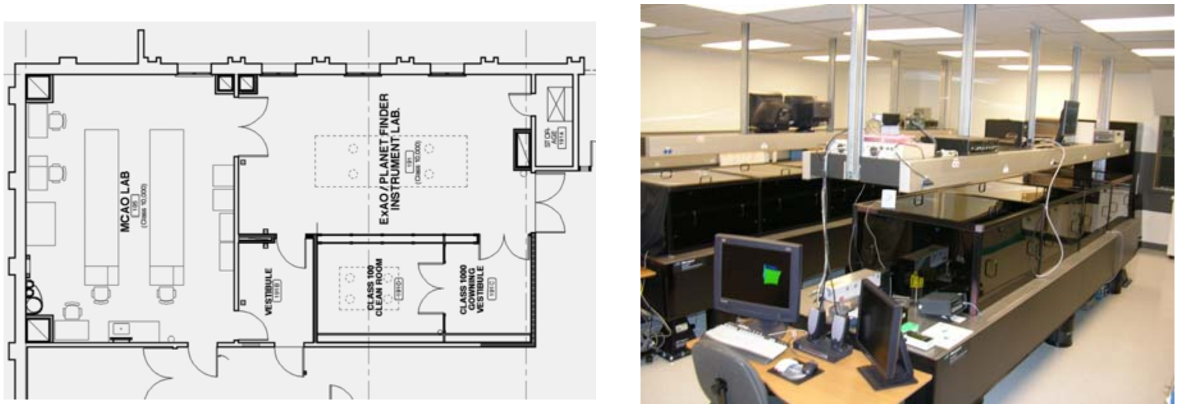

Figure 1. UCO/Lick Observatory Laboratory for Adaptive Optics

2. FACILITIES AND EXPERIMENTS

The laboratory is located on the Santa Cruz campus of the University of California in the Thimann Laboratories building (Figure 1). This location is close to the UCO/Lick Observatory headquarters facilities, the UCSC Astronomy Department, and the Center for Adaptive Optics (CfAO) on science hill on the UCSC campus.

The facility is designed to maintain a controlled temperature, dust, lighting, humidity, and vibration environment, which are crucial for precise optical measurements. The facility includes a 200 square foot class 100 clean room which will enable ultra-clean assembly of the final optical cells in a planet imaging instrument plus provide an environment for any other testing where scattered light from dust particles must be kept to a minimum.

Laboratory equipment includes a number of interferometers for testing devices and adaptive optics system concepts. A Fizeau interferometer is used to measure large optical components as well as small devices such as micro electro-mechanical systems (MEMS) deformable mirrors. A phase-shifting point diffraction interferometer (PSDI) based on a design used in EUV lithography optics testing is used in the Extreme Adaptive Optics testbed to measure wavefront quality down to 300 picometers rms. A quadrature polarization interferometer (QPI) of our own design takes interferograms at high speed to characterize the time response of adaptive optics devices. In addition to the interferometers, a differential image contrast microscope with precision metrology enables us to evaluate the fabrication quality of MEMS devices, coronagraphic masks, spatial filters, and optical slicer elements used in wavefront sensors.

2.1 Extreme Adaptive Optics for Extrasolar Planet Imaging

One of the grand challenges in the next decade of astronomy is to image and characterize planets outside of our own solar system. Presently over 100 extrasolar planets have been detected by indirect means such as by measuring radial velocity shifts of the parent star or analysis of the photometric curves of eclipsing systems. With a sensitive enough instrument that carefully controls the scattered light from the parent star, it is possible to detect and analyze the light from the planet directly[1].

To suppress the scattered light from the parent star due to wavefront aberrations from the Earth's atmosphere, a ground based planet imager must employ "extreme" adaptive optics, i.e. one with lots of actuators on its deformable mirror. A coronagraph must also be used to suppress diffraction of the starlight from the aperture (Figure 2). Our nominal extreme adaptive optics system design uses a micro-electromechanical system (MEMS) as the key component, the deformable mirror[2]. MEMS deformable mirrors place a large number of actuators in a very small space at reasonable cost per actuator (Figure 3).

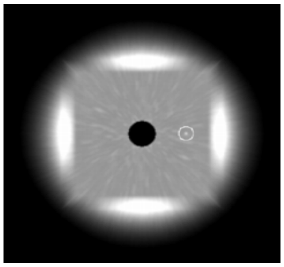

Figure 2. Simulation of a planet image using the Extreme Adaptive Optics Coronagraph instrument. Wavefront control by the deformable mirror carves out a dark planet discovery region around the central star. Light from the central star is blocked by a coronagraph (black spot) and an apodizing Lyot stop suppresses diffraction. 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. Streaks are residual speckles from calibration imperfections allowed in the instrument error budget.

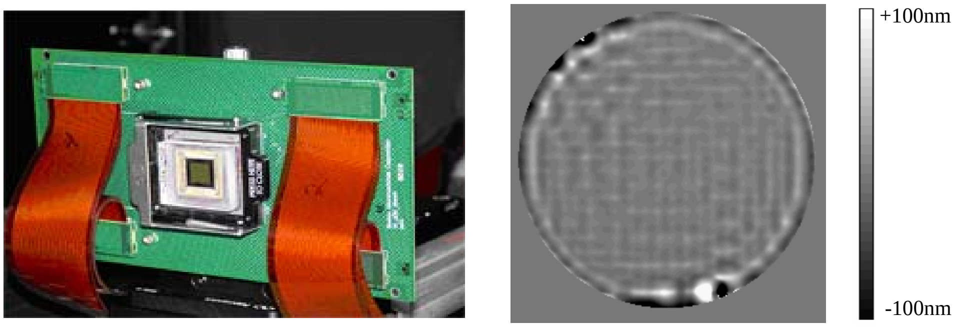

Figure 3. Left: the MEMS deformable mirror is shown in its mount. Right: grey-scale display of wavefront phase, as measured by PSDI, of a 9-mm diameter circular beam of light reflected off the central area of the MEMS. The MEMS device has a 10-mm square active area. An iterative algorithm using PSDI measurements determines the voltage commands required to achieve maximum flatness. The residual wavefront error visible, on the order of 5 nm rms, is mostly "print-through" of actuator mounting structure to the continuous mirror surface. This high spatial frequency ripple scatters light mostly outside of the discovery region in the final image.

The Extreme Adaptive Optics testbed consists of the MEMS device, the phase-shifting point diffraction interferometer, computer equipment to process the phase measurements and drive the deformable mirror, plus a

Hartmann wavefront sensor. Since the final instrument must use incoherent starlight to measure wavefronts for AO correction, we must demonstrate that the Hartmann sensor is able to measure the wavefront accurately enough to provide the needed high contrast correction. An innovation by a member of our team has led to a spatial filter modification to the Hartmann sensor which enables the dark discovery region for the planet to extend out to 1/ (2x Actuator spacing on the DM) away from the parent star[3]. Near-term upgrade plans call for adding a second pupil and Lyot coronagraph to this setup.

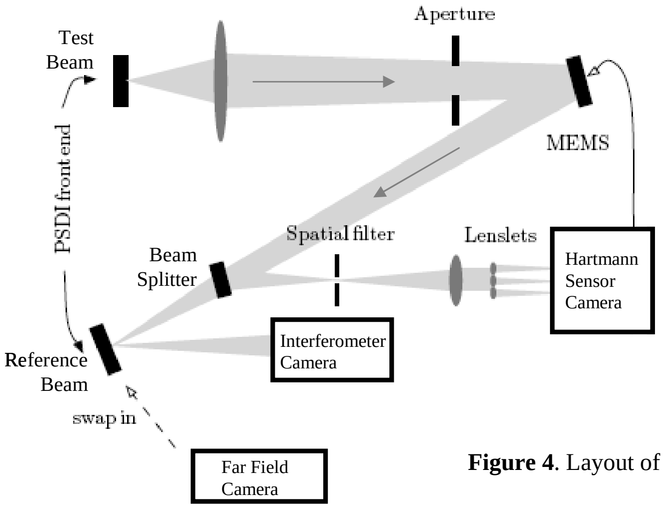

Figure 4. Layout of the extreme adaptive optics testbed.

The in collaboration with Lawrence Livermore National Laboratory, Herzberg Institute of Astrophysics, Jet Propulsion Laboratory, and a number of other institutions, the LAO team plans to build a 4,000 actuator extreme adaptive optics planet imaging coronagraph instrument for the Gemini 8 meter telescope. Members of the team are also involved with feasibility studies for a planet imager instrument on the proposed next generation large telescope for ground based astronomy, the Thirty Meter Telescope.

2.2 Multiple Guidestar Adaptive Optics for Next Generation Telescopes

Presently fielded adaptive optics systems use one deformable mirror, one wavefront sensor, and possibly one laser guidestar, and will correct images over a very narrow field known as the isoplanatic angle which is perhaps 10 arcseconds in good seeing. Multi-Conjugate Adaptive Optics (MCAO), or more broadly, multiple-laser guidestar tomography for AO-corrected imaging, enables diffraction-limited imaging on a wider field, and also overcomes the cone-effect error caused by laser guide stars being at finite altitude. Our research is targeted toward the next generation of “Extremely large” (30-meter class) ground based telescopes where the goal is about a one arcminute field.

The MCAO test bench is nearing its completion with system-integrated experiments slated to start in September. Individual components including spatial light modulator deformable mirrors, Hartmann wavefront sensors, and phase aberration plates have been fully characterized. In parallel, LAO is pursuing innovative adaptive optics system concepts in the areas of wavefront sensing and optimal wavefront control in separate experiments[4].

A new system concept, Multi-Object Adaptive Optics (MOAO) has emerged over the past year through our collaboration with the Thirty Meter Telescope project. MOAO provides an extremely wide field of AO correction (5 arcminutes on the Thirty Meter Telescope) that is ideally suited to multi-object spectrographs – a mainstay for extragalactic science programs on large telescopes. Our “MCAO” testbed has been designed to allow convenient switching between MCAO and MOAO configurations.

MCAO testbed layout. To perform laboratory experiments relevant to MCAO on a 30-meter telescope, one must scale 60 km of turbulent atmosphere and a 30-meter diameter telescope to fit on a room-size optical bench, while retaining similar geometric and diffractive optics behavior. This scaling has been a main consideration in the optical design and layout of the testbed.

Optical path – MCAO mode

The MCAO optical testbed layout is shown in Figure 5. Light enters the system via laser fibers emulating 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. We mentioned this interferometer earlier as one that takes interferograms at high speed. The MCAO testbed is designed to run in “closed loop” at a relatively quick pace (the testbed goal is 5 Hz sample rate) while the phase aberration plates are moved to simulate wind blown turbulence. This allows us to characterize the dynamic behavior of MCAO control algorithms[5,6].

The testbed is designed to handle up to 4 deformable mirrors, 8 laser guidestars, 4 tip/tilt guide stars, and a “science object” (point source for testing performance) deployable over the field.

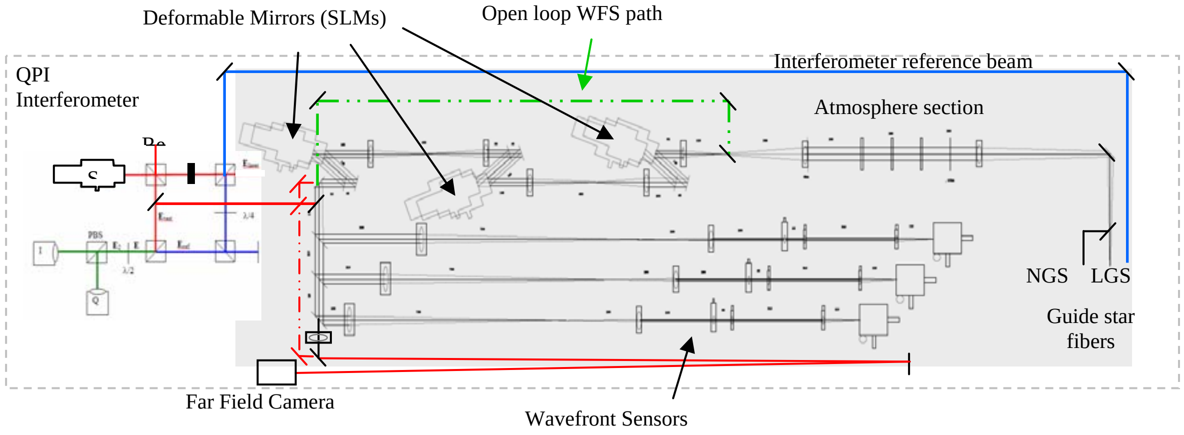

Figure 5. MCAO/MOAO Testbed

MOAO mode

The MCAO arrangement on the optical bench can be conveniently switched to an MOAO configuration (the green dotted line path in Figure 2). 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 3-D estimate of differential optical paths throughout the volume of atmosphere. Deformable mirror commands are derived by summing along ray paths through this volume corresponding to the science object directions.

The MOAO system runs in “open loop,” that is, the effect of AO commands to deformable mirrors are not sensed by the wavefront sensors. This puts additional demands on deformable mirror technology to respond accurately to commands without having to be re-measured. Tests designed to measure this property of MEMS deformable mirrors are ongoing in the PSDI interferometer.

3. COLLABORATIONS

The LAO provides a general purpose facility for investigating new AO system concepts and testing new component technologies. We are collaborating with a number of other programs within the astronomical community with the goal of improving the resolution of the next generation of telescope instruments.

In particular, we are collaborating with the Thirty Meter Telescope project, a UC, Caltech, NOAO(AURA), ACURA(Canada) consortium to develop the next generation large ground based astronomical telescope. The present baseline is to use adaptive optics on every one of the infrared instruments and “ground layer” adaptive optics on at least one visible light instrument. We are exploring the MCAO, MOAO and ExAO concept instrument architectures and spearheading the development of MEMS deformable mirrors.

The National Science Foundation’s Adaptive Optics Development Program (AODP), administered by the National Optical Astronomy Observatory (NOAO), supports multi-year research programs on advanced deformable mirrors, high dynamic range low noise wavefront sensors, sodium guidestar lasers, and computer algorithms for adaptive optics. Three of the six funded projects under this program include LAO participation in testing prototype components.

LAO staff has been engaged in helping to develop adaptive optics capability and technical training on the island of Maui. We are collaborating with Oceanit Laboratories assisting with their AEOS simulator testbed development at the Maui Research and Technology Center. We have also worked with Maui Community College to help set up a laboratory to train optics technicians.

4. SUMMARY

The UCO/Lick Observatory Laboratory for Adaptive Optics is working towards its goal of serving the astronomical community through forefront laboratory research in adaptive optics, providing key facilities for future giant telescope projects, and training the next generation of leaders in adaptive optics hardware and software systems.

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