

NSF Major Research Instrumentation Program
**Development of an Enhanced Adaptive Optics System and Infrared
Instrumentation for the Shane 3-meter telescope**

Second Year Report
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Research and Education Activities & Summary of Findings

In the second year of this project, we have taken the requirements from the science user community and results of performance prediction models as generated during year 1 and flowed them in to a final engineering design effort. We have now established the key aspects of the design and are presently moving forward into a final engineering stage. The optomechanical layout, adaptive optics control system design, bench automation systems, infrared camera design, and overall telescope mounting scheme have all been established. Most of the major AO system components have been specified and are either on order or delivered. The infrared detector array and its drive electronics have been delivered and we are close to receiving the wavefront sensor CCD and its fast readout electronics. We are now proceeding with development along three parallel paths: 1) system integration of the active adaptive optics components (wavefront sensor, deformable mirrors, control computer), 2) testing and programming of the infrared science detector array, and 3) final engineering of the optomechanical table, component mounts, and telescope mounting structure.

Adaptive Optics System Design and Configuration

The older facility Lick adaptive optics system has design parameters that enable diffraction-limited observing only in the $\lambda=2.0\ \mu\text{m}$ science band (astronomy K-band). The new system is designed to operate at the diffraction-limit over the broad range of near-infrared bands, $\lambda=1.0$ to $2.0\ \mu\text{m}$, covering astronomy J through K bands. The sampling on the DM, the wavefront sensor, and the science focal plane were all selected for the new system accordingly. We are taking advantage of several new technologies to extend science capabilities of adaptive optics to the shorter science wavelengths: 1) a micro-electro-mechanical system (MEMS) deformable mirror that provides high precision, go-to repeatability, and correction at high spatial frequencies, 2) a Hawaii-2RG infrared detector array which has a smaller pixel size and better quantum efficiency, enabling Nyquist sampling at the diffraction-limit in J band and extending sensitivity into the visible, 3) a laser that will have an optimized spectral and pulse format to provide a brighter guidestar return signal.

Figure 1 shows the map of deformable mirror actuators and Hartmann sensor subapertures as projected on to the primary mirror of the telescope. We chose to provide a selection of three settings for pupil sampling: 40 cm, 20 cm, and 10 cm. This allows for the variations in seeing conditions and guide star brightnesses under various observing scenarios and enables optimizing the science return over a wide range of conditions and observing wavelengths. The new laser guidestar will serve the mid scale, 20 cm, subaperture conservatively, and, in good seeing and sodium density conditions, will serve the 10 cm subaperture scale. The wavefront sensor camera optics and kinematic change-out mechanisms for switching scales are considerably far along in the design stage and will be completed within the next few months. This will enable work to proceed on integrating the wavefront sensor with the AO real time control system later this year.

The photo on the right side of Figure 1 shows the 1024-element (“Kilo-DM”) MEMS deformable mirror received from Boston Micromachines Corporation.

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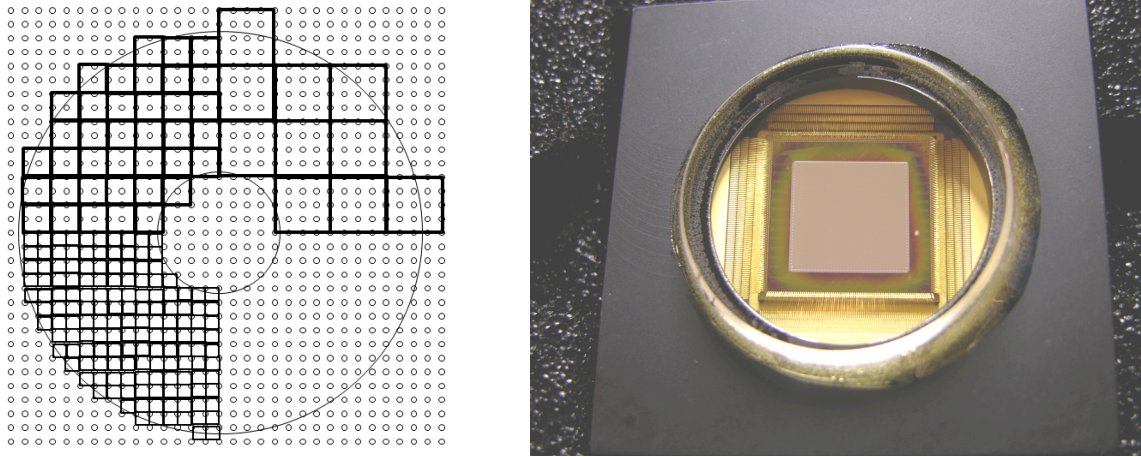


Figure 1. Left: Layout of actuators (small circles) and lenslets (squares) for ShaneAO, showing three selections of lenslet scale. Wavefront sensor sampling is selectable, depending on guide star brightness, with choices of 43cm, 21.5 cm, and 11 cm diameter. The largest of these, 43 cm, is the present AO system's subaperture size. The actuators are spaced on 11 cm centers mapped to the primary mirror. Since the MEMS device has predictable open loop behavior, the extra control degrees of freedom can be constrained when using courser wavefront sensing scales. The wavefront controller uses these constraints to tailor the spatial frequency content of the wavefront correction. Right: photograph of the front surface of ShaneAO's Kilo-DM MEMS device.

Measurements of the Shane Telescope System

We made measurements of the static aberrations of the Shane telescope this year with on sky tests using the current AO system's wavefront sensor. The telescope shows mostly astigmatism, which varies slightly with pointing angle of the telescope. About 2.5 microns peak-to-valley of a bias DM stroke will be needed to compensate for the static telescope figure. This large static aberration combined with the large amplitude low order modes of the turbulent atmosphere will exceed the MEMs device's limited stroke range. This led us to an AO system configuration that has a low-order woofer DM operating in tandem with the high-order MEMS DM. The woofer DM is a 52 degree of freedom magnetically actuated membrane mirror built by ALPAO. This mirror has an advantage that it can also correct the tip/tilt component of the wavefront, allowing this device to perform both the tip/tilt and low order wavefront correction roles. We have developed a woofer-tweeter control algorithm, involving cross-over of the low and high order spatial modes along with crossover of the low and high temporal frequency drive (the woofer has a limited temporal response) and have proven its efficacy in control loop analyses and simulations.

We also took measurements of the high-speed star wander as seen by the telescope in order to understand both the atmospheric component of tip/tilt, any wind induced shaking of the telescope, and determine if there are any troublesome vibration resonances of the telescope. The measured spectrum is shown in Figure 3, showing no apparent resonances. The "yarn-ball" plot next to it shows the x and y jitter components plotted against each other. In short, we saw no difficult resonances and the tip/tilt demands are well within the range of the woofer DM.

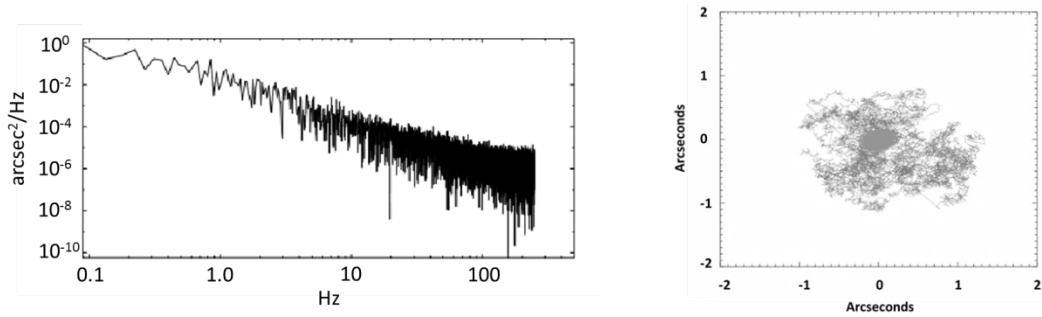


Figure 2. Left, jitter spectrum of a star, measured by the wavefront sensor in the current AO system (AO system turned off). The spectrum includes open atmosphere seeing plus any wind shake and vibration components. Right, a short (10 second) history of star wander in x and y.

Optomechanical System Design Progress

The AO system optical bench is to be mounted to the back of the telescope at the Cassegrain position. The Shane is an equatorial mount telescope (one of the largest such mounts ever built) providing a fixed sky coordinate system to the detectors mounted at the Cassegrain focus as the telescope moves to track earth’s rotation. However, a disadvantage of mounting an instrument at Cassegrain is the varying direction of gravity with respect to the instrument optical table and mounted components. This drives a requirement that the table be very rigid, that it is mounted kinematically to the telescope, and that all the mounts and stages on the optical bench are designed to tolerate the loads while remaining aligned to a diffraction-limited accuracy.

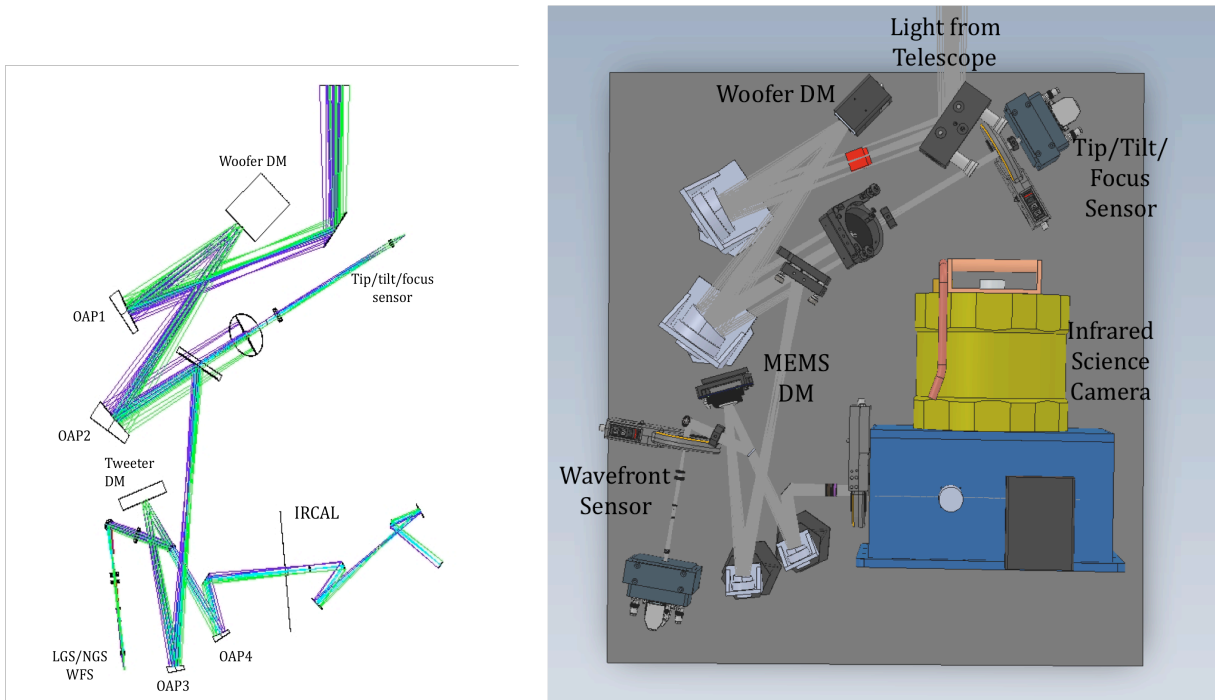


Figure 3. Optical design and layout of ShaneAO. The system consists of two DMs: a woofer (DM52) and tweeter (MEMS), both located at pupil image planes fed by optical relays labeled OAP#. The woofer also provides fast tip/tilt correction. IRCAL is the infrared science camera.

The ShaneAO bench design is configured around a very stiff support system providing kinematic attachment to the telescope (Figure 5). On the optical bench key component locations are held to precise relative position (e.g. tip/tilt

sensor focal plane with respect to science camera focal plane) so that long exposures are possible without the science object drifting across the science detector.

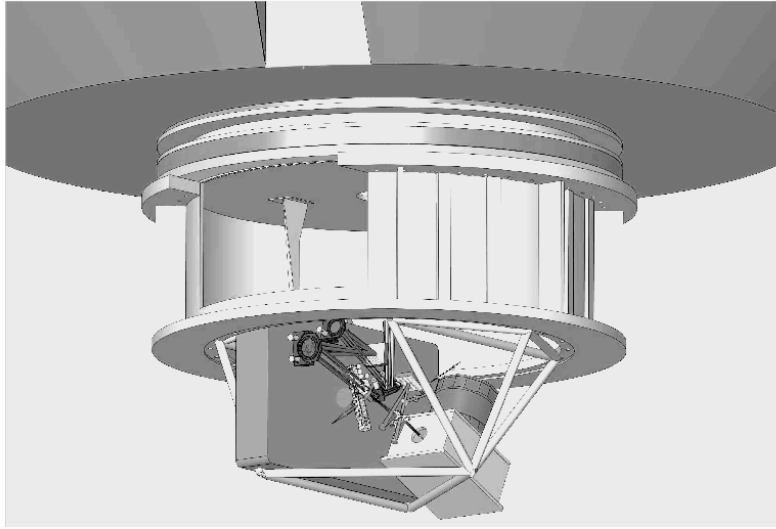


Figure 4. Rendition of the ShaneAO system mount design for the Cassegrain position on the 3-meter telescope. The space structure design constrains motion of the optical bench with respect to the telescope and defines a stable platform for the AO components. (Note: this image shows an old configuration of the components on the optical table, which is now superseded by the arrangement shown in Figure 3.)

The new AO system is also smaller than the existing one and tucks up closer to the primary. This permits the whole instrument to be rotated on the Cassegrain rotation stage, providing an additional option for science observation where a preferred sky coordinate orientation is selectable with respect to a spectrograph's dispersion axis or with respect to the atmosphere's natural dispersion.

Focus Sensing and Control Strategy

Laser guidestar operations require a natural tip/tilt star because the laser beacon itself, which jitters on its path up through the atmosphere, is not a suitable pointing reference for the stars on the celestial sphere. The laser guidestar is also not suitable as a long-term focus reference, since the mesospheric sodium layer in which the guidestar is formed slowly changes in mean altitude. We have designed the natural guide star tip/tilt sensor so that it is very efficient with the starlight, enabling dimmer stars and thereby wider science sky coverage, while at the same time is able to sense slow variations in focus over long time scales. The sensor design takes advantage of the fact that it is located downstream of the woofer DM, thus the tip/tilt star will be partially AO corrected, enhancing the star position sensing accuracy. The slow focus sensing is accomplished by optically introducing a very small amount of static astigmatism into the star image. An out of focus condition then manifests itself with an elliptical shape of the star image. Slow focus is fed back initially to the woofer DM and then offloaded eventually to the z-position of the AO wavefront sensor so as to drive images of natural stars to best focus continually as sodium layer height varies. One of the critical opto-mechanical design challenges is making sure this tip/tilt/focus sensor is rigidly referenced to the science camera focal plane.

Infrared Science Detector

The science detector is a Hawaii-2RG detector from Teledyne Scientific and Imaging Corporation. In ShaneAO, we will only need to use one 1k x 1k quadrant of this device to sample the AO corrected field at diffraction limit for all the target science wavelength bands, so we purchased a device that is guaranteed to be science grade on one of the quadrants. This strategy allowed us to save considerable cost in the purchase of the detector. Also, maintaining the existing science field of approximately 20 arcseconds square allowed us to reuse the IRCAL dewar with minimal modification, saving considerable redesign effort and cost.

The Hawaii-2RG device, along with drive electronics, an electronically equivalent dummy device, and a development kit, arrived two months ago and is presently undergoing evaluation in a test dewar in our optical shops (Figure 5). The

UCLA infrared laboratory will be assisting us in deploying the system with engineering help on all aspects of infrared camera design and with programming of the desired set of scientific data readout modes. UCLA has recently fielded two instruments using this same infrared array: the MOSFIRE spectrograph for Keck Observatory and the Gemini Planet Imager integral field spectrometer.



Figure 5. Hawaii-2RG infrared science detector being unpacked for inspection at the Lick Observatory detectors laboratory by graduate student Rosalie McGurk.

Laser Guidestar

Although technically not part of the NSF MRI project, Lick Observatory plans to install a new guidestar laser to operate with the ShaneAO system. The laser, constructed at Lawrence Livermore National Laboratory (LLNL) with development funding from the NSF Center for Adaptive Optics and the NSF Adaptive Optics Development Program, will provide 10 watts of sodium wavelength (589 nm) output at an optimal pulse and spectral format designed to maximize the guidestar signal return. The laser is (unfortunately) still at LLNL awaiting the relevant government agency approval for shipping. It will first be delivered to our laboratory at UC Santa Cruz for final engineering in preparation for installation at the observatory. LLNL laser physicist Dr. Jay Dawson will assist us in the initial set up and operations of this laser. It will be mounted near the telescope polar axis and fed via fiber to the existing laser launch telescope on the Shane telescope.

Graduate student Rachel Rampy has been evaluating guidestar performance as a function of laser parameters in consultation with Dr. Ron Holzlohner of the European Southern Observatory (ESO) and Prof. Dmitry Budker of UC Berkeley who are experts in the field of sodium atom laser excitation. We expect to achieve between 5 and 10 times the guidestar brightness of the current dye laser (Figure 6).

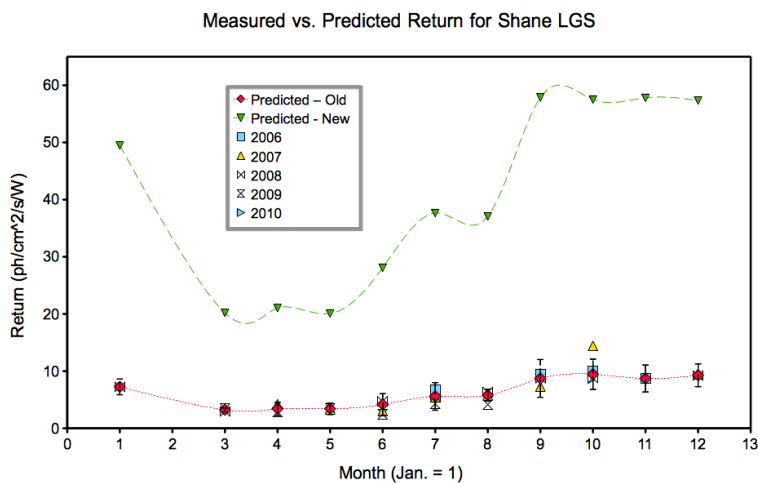


Figure 6. Laser guidestar return modeling for Lick Observatory. We used a computer model, developed by ESO and UC Berkeley researchers, for the sodium atom's fluorescent excitation by laser light to derive predictions of guidestar return signal using both the present dye laser and the new fiber laser. Data points from guidestar measurements at Lick using the dye laser overlay the dye laser predictions. The one unknown, seasonally varying sodium atom density in the mesosphere, is adjusted to fit that data. The calculations predict significant improvement in guidestar brightness with the new fiber laser.