

Villages: an on-sky visible wavelength astronomy AO experiment using a MEMS deformable mirror

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ABSTRACT

The MEMS-AO/Villages project consists of a series of on-sky experiments that will demonstrate key new technologies for the next generation of adaptive optics systems for large telescopes. One of our first goals is to demonstrate the use of a micro-electro-mechanical systems (MEMS) deformable mirror as the wavefront correcting element. The system is mounted the 1-meter Nickel Telescope at the UCO/Lick Observatory on Mount Hamilton. It uses a 140 element (10 subapertures across) MEMS deformable mirror and is designed to produce diffraction-limited images at wavelengths from 0.5 to 1.0 microns. The system had first light on the telescope in October 2007. Here we report on the results of initial on-sky tests.

Keywords: Astronomical Adaptive Optics, Deformable Mirrors, Atmospheric Wavefront Control

1. INTRODUCTION

The Lick Observatory has constructed an experimental visible light adaptive optics system for use on the 1 meter Nickel telescope at Mount Hamilton with the purpose of demonstrating MEMS deformable mirrors as well as several other new AO technology concepts in an observatory environment. The MEMS-AO/Visible Light Laser Guidestar Experiments (Villages) project has two goals in its first phase: 1) demonstrating that a MEMS deformable mirror can correct stellar images to the diffraction limit in a closed loop AO system, 2) demonstrating that a MEMS can be used reliably in an open-loop, or “go-to” control on-sky. We have achieved goal 1 during this past year’s first-light experiments (October and November 2007) and we expect to achieve goal 2 this spring as a follow on to successful laboratory tests reported in a companion paper¹.

Phase 2 of the Villages project involves projecting an uplink AO corrected laser and demonstrating that uplink correction produces a much smaller laser guidestar spot than current laser guidestar systems. The smaller spot will enable accurate wavefront sensing with a minimum of laser power. The uplink corrected beam will be first reflected of a DM that pre-corrects for the atmospheric aberrations in the uplink path, then projected out the 1-meter aperture. These experiments are expected to take place initially in the Fall of 2008, after we receive a suitable laser.

MEMS actuators have very reliable and predictable response to applied command voltages². For this reason, it is possible 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 using independent deformable mirrors for each science path. Furthermore, in a laser guidestar AO system independent MOAO correction of off-axis tip/tilt stars will have a large impact on sky coverage (percentage of the sky available for diffraction limited astronomy) since it allows the use of the denser field of faint tip/tilt stars. The MEMS-AO/Villages instrument is essentially a demonstration MEMS based single-arm MOAO system.

Table 1 summarizes our main experimental goals and the relevance to astronomical AO design over the next 2-year time frame of the program.

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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 |

2. VILLAGES OPTICAL DESIGN AND CONFIGURATION

Figure 1 shows a conceptual layout of the Villages optical system. The light coming in from the telescope first reflects off a fast tip/tilt mirror and then is split 50/50 with one path reflecting off of the DM and one bypassing it. These two beams are recombined at the second splitter but are slightly offset in position so that side-by-side Hartmann images are obtained on the wavefront sensor camera. The post DM wavefront is used in closed loop operating mode. This mode acts in the traditional manner to drive the wavefront sensor to a null reading according to a prior calibration from a flat wavefront. The bypass path provides a way of directly sensing the uncontrolled atmospheric phase without the DM in the loop. We use this to test the open-loop control architecture. Successful open loop control requires the measurement of the wavefront to be accurate over the full dynamic range of possible atmospheric aberrations and accurate actuation of the DM to full dynamic range, without the benefit of feedback, so the controller incorporates non-linear lookup compensation for the wavefront sensor and the plate-equation MEMS DM model as in the real-time processor. Both sets of Hartmann sensor readings are available simultaneously regardless of operating mode so they can function as monitors of each other's performance. For example, in open loop operation, the post DM sensor data will indicate how well the wavefront is kept flat by the open loop controller.

The second splitter also sends a fraction of each of the two beams to the far-field science imaging camera, which is a science grade cooled CCD (Lick dewar 2). This provides a simultaneous measurement of pre and post compensated point spread function.

The optics bench has been designed so that incoming light can share the aperture with an outgoing laser beam. The laser beam first reflects off of its own deformable mirror in order to attain a precompensated wavefront for propagation through the atmosphere. If properly corrected and focused, the beam will form a diffraction-limited spot at the sodium layer, about 10cm in diameter. Through the use of appropriate dichroic splitters, the return laser light can be sent to one or the other channel of the wavefront sensor or to the science CCD. In experiment 3 the idea is to operate the AO system closed loop on a natural guide star, so the wavefront sensor sees the natural guide star and the DM is compensating incoming wavefronts (both splitter 1 and 2 transmit the sodium wavelength). The open-loop wavefront sensor provides the wavefront for the laser uplink DM. An image of the uplink and downlink corrected laser guide star spot is then imaged on the science CCD where, since the AO system is providing diffraction limited imaging at the visible wavelength of the laser, will confirm that the uplink system worked to produce a small spot on the sodium layer.

In experiment 4 the received laser light is sent to the wavefront sensor and the natural starlight to the science camera.

For the laser guide star experiments we must use a pulsed laser so that guide star light from the sodium layer can be time-gated into the receiving system without contamination from the light scattered from aperture shared elements and the lower atmosphere (Rayleigh backscatter). There is a retro path for the laser in order to sample a small portion of the outgoing light and feed it to the Hartmann sensor, but otherwise the outgoing light is blocked from the receiver path with a chopper wheel timed to the laser pulses. It is just a matter of convenience that we share the aperture with the laser in the Villages experiment, so that we can perform the experiment using only a single 1-meter telescope. A future AO system would use uplink correction and a separate 1-meter projector while receiving in its 30

meter or larger aperture. In that case it would not be necessary to use a pulsed laser although there are other potential advantages to using pulsed lasers in future AO systems³.

Figure 2 shows the physical layout on the optical bench, which incorporates practical packaging considerations. Figure 3 shows its mounting at the Cassegrain focus of the Nickel 1-meter telescope.

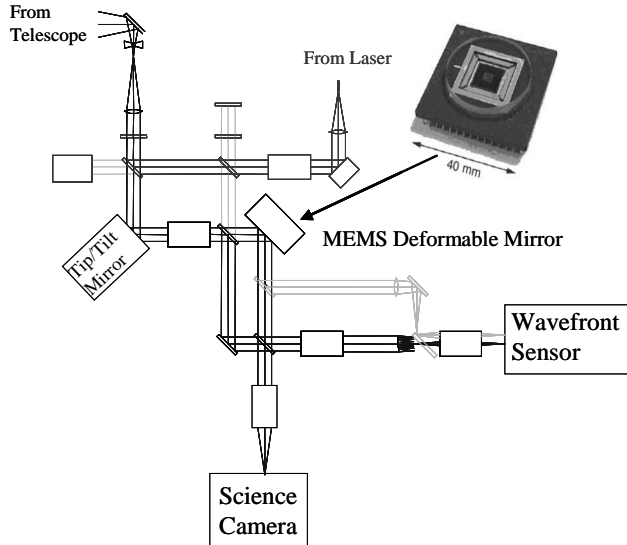


Figure 1. MEMS-AO / Villages system. The system employs a 140 actuator MEMS deformable mirror and fits on the back of the Lick Observatory 1-meter Nickel telescope.

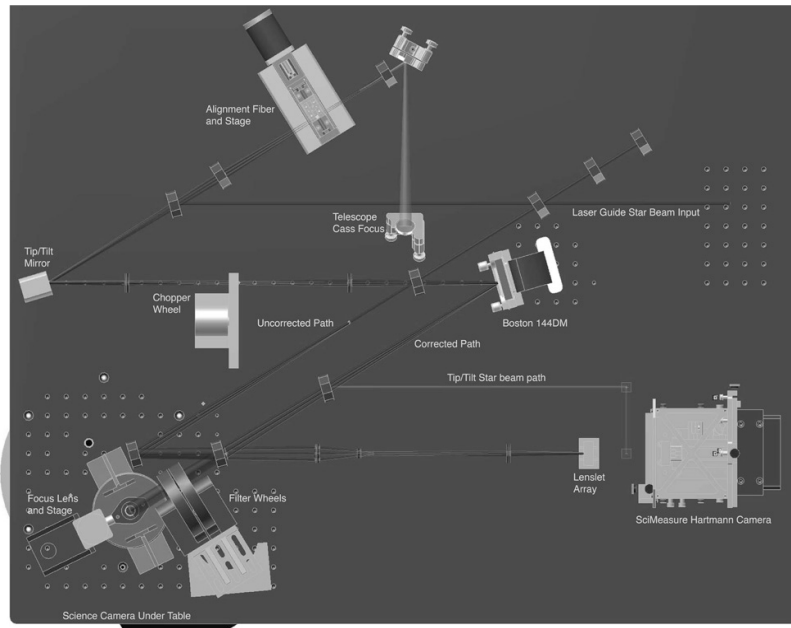


Figure 2. Top view of the Villages optical bench.

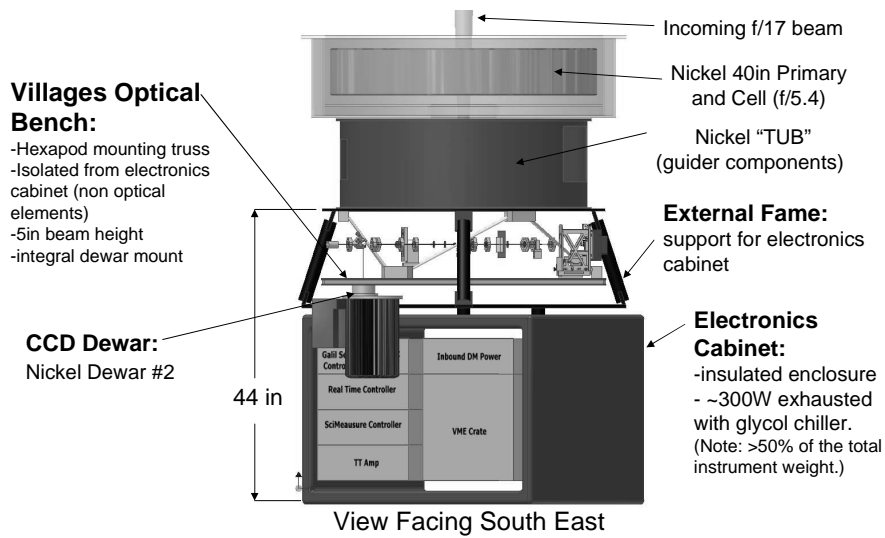


Figure 3. Side view of Villages instrument as mounted on the Nickel telescope.



Figure 4. Top down view of Villages optical bench during laboratory I&T.



Figure 5. Optical assembly under test. A display of the Hartmann dots from a test beam shows on the monitor.

The Hartmann wavefront sensor geometry for Villages is matched to the 140 element MEMS deformable mirror, with 9 subapertures spaced across the 1-meter aperture. Taking into account the secondary obscuration and round pupil of the telescope, 60 subapertures are illuminated and 84 DM actuators are in the illuminated beam. The subaperture sampling is 11 cm, which is matched to the coherence patch size (r_0) of the atmosphere which is typically about 11-12 cm at Mt Hamilton at $\lambda=0.5$ micron wavelength. The Hartmann sensor camera is an 80x80 pixel E2V CCD chip in a SciMeasure camera. Each of the four 40x40 quadrants can support a Hartmann image (see Figure 6); two are used for the pre and post DM compensated guidestar light respectively, a third is used for tip/tilt sensing, and the fourth quadrant is available for outgoing laser sensing.

The science camera sees two images as shown in Figure 7. This image is a diffraction-limited picture of the internal calibration source. The beam that has reflected off of the MEMS shows a diffraction pattern, a regular grid of dots due to the micro surface roughness of the MEMS device. The face sheet tends to have a residual impression of the underlying actuator structure remaining from the MEMS manufacturing process and since the print through repeats at the actuator spacing, it produces a regular pattern of dots in the far field. These dots are generally about 1/1000 the brightness of the central beam.

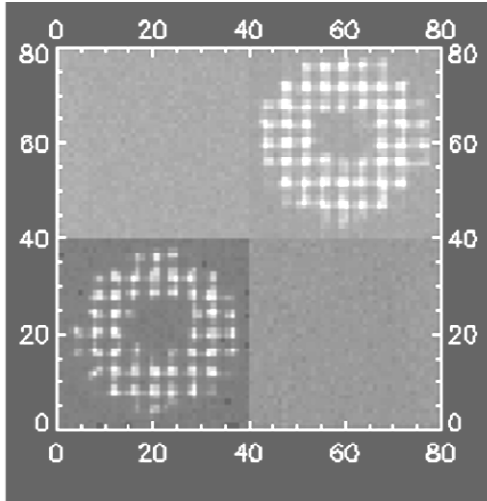


Figure 6. Hartmann sensor geometry showing Hartmann images from the DM corrected (upper right) and DM bypassed (lower left) beams.

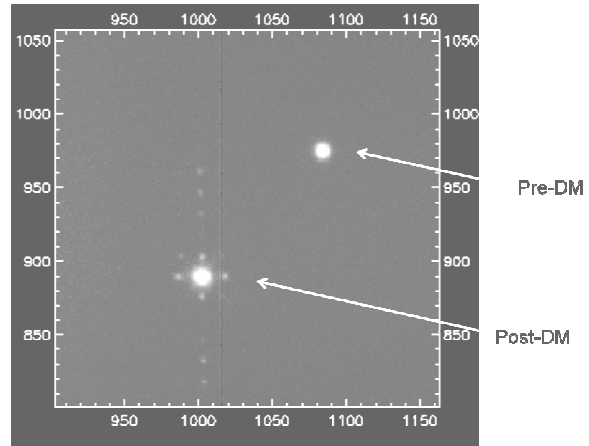


Figure 7. Science camera image of the two beams coming from a calibration source. The post DM beam shows the diffraction due to surface roughness of the MEMS face sheet.

3. FIRST LIGHT RESULTS

The Villages instrument was installed and commissioned on the Nickel telescope in October 2007. We had two three-night runs on the Nickel telescope in October and November of 2007. 3 of these 6 nights were weathered out, so at this point we have a total of 3 nights on sky. Systems operated well and the physical package, designed to be mechanically quite rigid, was well matched to the telescope, enabling us to begin tests right away. Initial alignment and testing was done with a flat mirror and fiber test source. The MEMS needs about 800nm of actuation to flatten its surface from a mostly focus unpowered shape. Here the MEMS showed its advantage over traditional piezo actuated DMs by repeatedly going to a flat state with a command voltage vector saved from prior laboratory measurements. The same voltage vector was used to flatten the mirror during both runs and is still used today. No actuator drift or hysteresis behavior is evident.

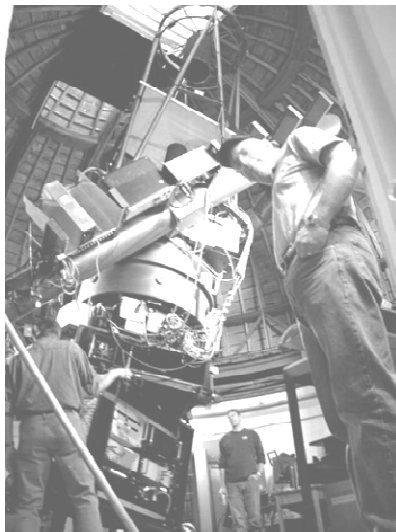


Figure 8. a) Villages installation on the Nickel 1-meter telescope at Mt Hamilton. b) Members of the Villages team in the control room at first light: L-R: Mark Ammons, Donald Gavel, Darren Dillon, Bryant Grigsby, Katie Morzinski.

On the second night (October 10) we ran the AO system in closed loop on a bright star near zenith, obtaining about 4% Strehl in I band ($\lambda=0.9\mu\text{m}$). It turns out that the real time controller had a bug in a piece of code designed to recover from saturated actuators. The bug caused the DM to operate at a wrong bias, forcing it near one edge of its dynamic range and resulting in a high percentage of the actuators running into saturation while operating closed loop. We corrected the problem by the second run in November and were able to achieve up to 25% Strehl ratio in I band (169 nm rms residual wavefront error). Figures 9 and 10 show some of the Strehl performance results. Several other minor glitches with system automation, shutter control, etc. were also corrected during these commissioning runs.

The MEMS device worked flawlessly and met our Experiment 1 goals of demonstrating their suitability and robustness for astronomical AO. Our error-budget predicted goal for the system is a closed-loop Strehl of 0.3 in V band (87 nm rms residual wavefront error) under “ordinary” ($r_0=11$ cm) seeing conditions. We are some distance from this target but have identified a number of improvements which can help us reach it. These are:

- 1) Decreasing the control latency and perhaps increasing the system frame rate and control bandwidth with a new, faster, real-time processor card. We have received this card but haven’t yet installed it into the controller.
- 2) Re-machining and aligning the focal plane stops in the wavefront sensor. These stops set the field of view to match the 4x4 pixel grid assigned to each Hartmann subaperture to prevent crosstalk between the subapertures. Villages is particularly sensitive to this because of the tight packing of subapertures on the wavefront sensor CCD which does not allow space for “guard bands” of pixels.
- 3) Improving the internal calibration. Presently the internal Strehl (with the calibration source) on the MEMS path is about 0.5 at $\lambda=635\text{nm}$ (~ 84 nm rms wavefront error) and about 0.8 (~ 48 nm rms wavefront error) on the bypass path. Independent measurements have confirmed that we have flattened the MEMS to on the order of 20 nm rms wavefront, so the residual, about 60nm or $\lambda/10$, we ascribe to an extra optic, a splitter for the tip/tilt/PSF star, in the DM corrected path, the different relative paths through the other splitters, and diffractive losses due to the surface roughness of the MEMS. One approach to improving internal calibration is to use an iterative image sharpening technique, where we adjust Zernike modes on the DM so as to maximize Strehl of the PSF in the science camera.

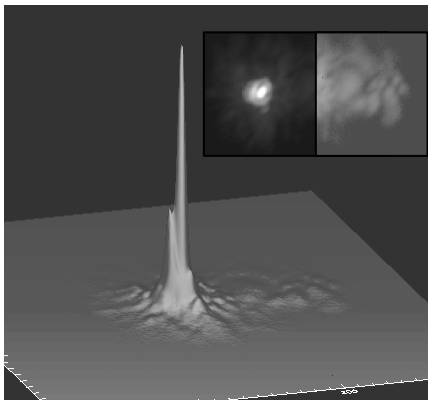


Figure 9. Simultaneous images of DM corrected and uncorrected star α -Aurigae in I band ($\lambda=0.9 \mu\text{m}$). Surface plot is linear scale. Inset images are log-stretched grey scale.

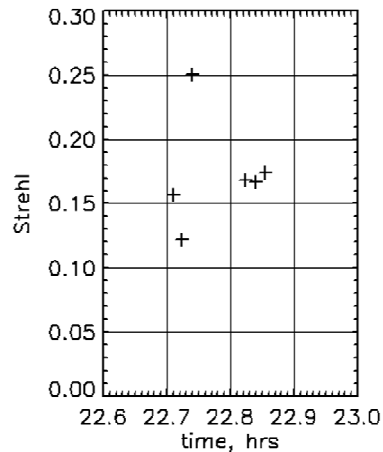


Figure 10. Strehl ratio over several short exposure (50 msec) images of α -Aurigae in I band.

We have not yet done any of the open loop control or laser experiments. Open loop control recently passed a series of laboratory tests reported in a companion paper at this conference¹. These indicate that we expect less than 30 nm rms wavefront error due to open loop DM modeling error in the dynamic range of wavefront aberrations at the observatory. With installation of the newly calibrated reconstruction matrix and nonlinear lookup tables, we expect to test the open loop controller on the telescope in March 2008.

Laser uplink tests are awaiting delivery of an experimental pulsed laser, nominally scheduled for mid to late 2008 installation at the telescope. We have yet to select an uplink DM for the laser but this will most likely be a membrane mirror coated with a high reflectively laser line coating to minimize the power loss on the DM.

4. CONCLUSIONS

The Villages experiment is well on its way to demonstrating the feasibility of using MEMS deformable mirrors in astronomical adaptive optics systems. MEMS are smaller, have lower cost per actuator, and have superior properties such as open-loop controllability, that make them an attractive alternative to traditional piezo-actuated deformable mirrors now in common use. We've closed the loop on starlight and corrected to reasonable Strehl at CCD wavelengths and are on the way to demonstrating high-Strehl corrections at visible wavelength bands. This will enable uplink corrected laser guide star experiments in the coming two years.

ACKNOWLEDGEMENTS

This work is supported by the Gordon and Betty Moore Foundation through their generous grant forming the Laboratory for Adaptive Optics at U.C. Santa Cruz. The work of graduate student Katie Morzinski was supported under the Michelson Graduate Fellowship for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the United States Government under a Prime Contract between the California Institute of Technology and NASA. Additional support was provided by a minigrant from the Institute of Geophysics and Planetary Physics through Lawrence Livermore National Laboratory. This research was supported in part by the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement No. AST-9876783, and directed by Claire E. Max.

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