Final Report for Period: 09/2007 - 08/2008 **Submitted on:** 11/03/2008

Principal Investigator: Gavel, Donald T. **Award ID:** 0649261

Organization: U of Cal Santa Cruz

Submitted By:

Gavel, Donald - Principal Investigator

Title:

MEMS in Astronomical Adaptive Optics Visible Light Laser Guidestar Experiments

Project Participants

Senior Personnel

Name: Gavel, Donald

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Severson, Scott

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Bauman, Brian

Worked for more than 160 Hours: No

Contribution to Project:

Brian Bauman did the optical design work and helped to define some of the on-sky experiments

Post-doc

Graduate Student

Name: Morzinski, Kathleen

Worked for more than 160 Hours: No

Contribution to Project:

Katie Morzinski did initial studies of the science cases for the Villages experiment. She is involved in characterizing the MEMS deformable mirror and developing the algorithm for the open-loop experiments.

Name: Ammons, Mark

Worked for more than 160 Hours: No

Contribution to Project:

Mark Ammons did initial studies of the science cases for the Villages experiment and led experiments to analyze the static figure of the primary mirror of the Nickel 1-meter telescope on which Villages is to be mounted. He is presently working on methods of calibrating the wavefront sensors to the precision needed for open-loop control experiments.

Undergraduate Student

Technician, Programmer

Name: Lockwood, Chris

Worked for more than 160 Hours: No

Contribution to Project:

Chris Lockwood did the mechanical design of the mounting of the optical bench and electronics racks to the telescope as well as the design and layout of subcomponents and optics mounting hardware on the optical bench.

Name: Dillon, Daren

Worked for more than 160 Hours: No

Contribution to Project:

Daren Dillon assembled the optical bench and its components and optically aligned the system.

Name: Reinig, Marc

Worked for more than 160 Hours: No

Contribution to Project:

Marc Reinig did the electronics design work and is the lead programmer for the operational software including real-time adaptive optics control system and optical bench automation control.

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities:

Findings: (See PDF version submitted by PI at the end of the report)

see attached file, which summarizes activities and findings

Training and Development:

Two graduate students in astronomy have been active in the Villages system development and on-sky experiments. They were initially involved in modeling of expected performance of the visible light AO system under typical seeing conditions at Lick. They then performed Hartmann mask experiments at the Nickel telescope to measure the figure of the primary mirror (AO correction needs to compensate this as well as the atmosphere). One student (Morzinski) then worked in the laboratory to calibrate the response of the MEMS deformable mirror for open-loop control. These calibrations were used successfully in the first open-loop on-sky experiments. The second student (Ammons) modeled the nonlinear response of the Shack-Hartmann wavefront sensor in the presence of full atmospheric turbulence, and tested these calibrations in on-sky tests. Ammons has also helped to define future science programs for the Villages laser guide star system.

Outreach Activities:

Journal Publications

Morzinski, KM; Harpsoe, KBW; Gavel, DT; Ammons, SM, "The open-loop control of MEMS: Modeling and experimental results - art. no. 64670G", MEMS Adaptive Optics, p. G4670, vol. 6467, (2007). Published, 10.1117/12.71042

Gavel, Donald; Ammons, Mark; Bauman, Brian; Dillon, Daren; Gates, Elinor; Grigsby, Bryant; Johnson, Jess; Lockwood, Chris; Morzinski, Kathleen; Palmer, David; Reinig, Marc; Severson, Scott, "Visible light laser guidestar experimental system (Villages): on-sky tests of new technologies for visible wavelength all-sky coverage adaptive optics systems", Proceedings of the SPIE, p. , vol. 7015, (2008). Published,

Grigsby, Bryant; Lockwood, Chris; Baumann, Brian; Gavel, Don; Johnson, Jess; Ammons, S. Mark; Dillon, Daren; Morzinski, Katie; Reinig, Marc; Palmer, Dave; Severson, Scott; Gates, Elinor, "ViLLaGEs: opto-mechanical design of an on-sky visible-light MEMS-based AO system", Proceedings of the SPIE, p. , vol. 7018, (2008). Published,

Ammons, S. Mark; Gavel, Donald T.; Dillon, Daren R.; Reinig, Marco; Grigsby, Bryant; Morzinski, Katie M., "Application of Hartmann linear calibrations to ViLLaGEs", Proceedings of the SPIE, p. , vol. 7015, (2008). Published,

Morzinski, Katie M.; Gavel, Donald T.; Norton, Andrew P.; Dillon, Daren R.; Reinig, Marco R., "Characterizing MEMS deformable mirrors for open-loop operation: high-resolution measurements of thin-plate behavior", Proceedings of the SPIE, p. , vol. 6888, (2008). Published,

Books or Other One-time Publications

Web/Internet Site

URL(s):

http://lao.ucolick.org/twiki/bin/view/Villages/WebHome

Description:

This web site has the proposal text and the PDR and CDR documentation for the Villages project. There is also a movie of the optical bench under assembly in the laboratory.

Other Specific Products

Contributions

Contributions within Discipline:

Our laboratory experiments with the MEMS deformable mirror established a technique for controlling the mirror in open-loop to an accuracy of less than 17 nanometers rms surface, which is sufficient for visible wavelength adaptive optics correction. This performance has now been validated on-sky with the successful demonstration of open-loop adaptive optics wavefront correction with the Villages system. The on-sky demonstration has enabled designs to proceed with lower risk for AO instruments on large aperture telescopes that rely on open-loop wavefront control. The Keck 10 meter telescope Next Generation Adaptive Optics system concept uses open-loop control as a baseline for its multi-object spectrograph and for sharpening the tip/tilt stars (the later increases sky coverage by making dimmer stars suitable for tip/tilt sensing). The Villages on-sky result was timely, in time for presentation at the Keck NGAO System Design Review in April, 2008.

Contributions to Other Disciplines:

Contributions to Human Resource Development:

The Villages experiment has proven to be an inspiration to staff and graduate students involved, helping their career and education goals. One staff member has advanced from assistant development engineer to senior development engineer. One graduate student has advanced to PhD candidacy based partially on his work on Villages. Another graduate student has been awarded the Michelson fellowship, again based partly on her participation in Villages.

Contributions to Resources for Research and Education:

The outcome of the Villages experiment will be the technologies and techniques to implement both visible science wavelength AO and MEMS-based AO systems. This will bring to the experience base and therefore retire the risk of key components of next generation AO systems which are now being designed for the Keck 10-meter telescope and the proposed Thirty Meter Telescope.

Contributions Beyond Science and Engineering:

The work we are doing is of primary interest to the makers of MEMS deformable mirrors who are interested in supplying a potentially large number of such mirrors in future AO systems.

Categories for which nothing is reported:

Organizational Partners

Activities and Findings: Any Research and Education Activities

Activities and Findings: Any Outreach Activities

Any Book

Any Product

Contributions: To Any Other Disciplines

Final Report on the Villages Phase 1 Experiments

"MEMS in Astronomical Adaptive Optics Visible Light Laser Guidestar Experiments" (ViLLaGEs) was funded with an NSF Small Grants for Exploratory Research (SGER) award, #0649261, and was completed in the period September 15, 2006 through August 31, 2008. The NSF award for a total of $200,000 was used to construct the adaptive optics instrument and perform the on-sky experiments. The Lick Observatory provided the telescope facility and mountaintop observing support. Publications resulting from this award are references 2, 3, 7, 8, and 9.

Villages goals under the SGER grant were twofold: 1) prove that a new miniature deformable mirror based on micro-electro-mechanical systems (MEMS) technology is feasible for on-sky observing at an astronomical observatory site, and 2) taking advantage of the inherent non-hysteretic behavior of these devices show that open-loop wavefront control is possible. Open-loop control opens up a range of options for next generation AO system design including the ability to place the DM in multi-object spectrograph channels or to use it to sharpen tip/tilt stars in order to improve sky coverage.[1] These applications are enabled by the fact that since the DM is open-loop controllable it can be placed in positions of the instrument optical train where laser guidestar light is not available to probe its surface.

The MEMS-based adaptive optics system was constructed in 2006-2007 and mounted at the Nickel 1-meter telescope on Mt Hamilton in October 2007 where it now resides permanently. In monthly experiment runs we demonstrated first closed-loop diffraction-limited imaging then open-loop diffraction-limited imaging in V through I bands.[2] The open-loop wavefront control performed better than expected, exhibiting for example superior (temporal control) bandwidth than closed-loop control. All terms of the predicted error budgets were validated except for that associated with telescope vibration, which is now the limit to performance but against which we are making significant progress through a noise-cancellation approach. The AO system consistently produces 0.2 arcsecond full-width half-maximum images in 1 to 1.3 arcsecond seeing conditions.

Construction of the Instrument

The Villages system was built up on a 0.9 m square breadboard, which is mounted via a hexapod space frame to the Cassegrain mount of the telescope (Figure 1).[3] The optical path is shown in Figure 2. Light from the telescope goes first to a fast tip/tilt mirror, then to a splitter which sets up two alternative paths to the wavefront sensor and science camera, one which is reflected off the deformable mirror and one which is not. A second splitter/combiner allows switching or sharing of the two beams on wavefront sensor and science CCD. The two beams (reflected and not reflected off the DM) are routed to separate quadrants of the wavefront sensor detector, which enables simultaneous open and closed loop wavefront sensing. The control software can be configured to drive off of either of the sensed wavefronts. The path to the science camera after the second splitter includes wave band selection filters. In a near-future upgrade (early 2009) a Lyot coronagraph will be inserted in this path.

Figure 1. The Villages Adaptive Optics breadboard is attached to the Cassegrain mounting position of the Nickel Telescope. The electronics cabinet houses readout electronics for the wavefront sensor, the wavefront reconstruction computer, and the drive electronics for the MEMS deformable mirror.

The deformable mirror is a 144-actuator Boston-Micromachines MEMS device. This device has a continuous face sheet driven by independent electrostatic actuators. The diagram in Figure 3 shows the concept of actuation and face-plate attachment. The influence function is over a local neighborhood (a radius of 2 actuator separations) and is nearly equivalent for every actuator, so all 144 Fourier modes are available for wavefront control. The 1-meter diameter telescope pupil is mapped on to 3.6 mm of the device, or approximately 9 actuator separations across. This particular device has a total of 3 microns deflection capability, or 6 microns of wavefront control range, which is plenty for typical seeing conditions and a 1 meter aperture. However, larger aperture telescopes have larger displacement stroke requirements. The present generation of continuous face-sheet MEMS like this BMC mirror can be configured for up to 6 microns surface deflection, which would be sufficient for a 10 meter telescope. Larger apertures like the 30 meter may require a second "woofer" stage to cover the full dynamic range. Fortunately, the atmospheric turbulence has most of its optical path deviation concentrated in the lower spatial frequencies, hence a woofer-tweeter arrangement, where the woofer has higher stroke but fewer degrees of freedom, is an option.

The wavefront sensor uses a 80x80 pixel Marconi CCD39 device packaged in a "little-Joe" camera package constructed by SciMeasure Corporation. At the time this was the most sensitive and lowest read noise high-speed camera available. The 80x80 pixel format is divided into four 40x40 wavefront sensing quadrants. Three of the quadrants are presently used: one for open loop sensing (the beam that bypasses the DM), one for closed loop sensing, and one for tip/tilt sensing. The fourth quadrant is available for sensing the outgoing laser beam in phase 2 experiments. Wavefront sensing is the traditional Hartmann sensing technique, with a 4x4 grid of pixels assigned to each Hartmann spot on a 9x9 grid of Hartmann spots covering the telescope pupil. The 9x9 grid samples the wavefront at 11 cm, roughly the average value of r_0 in the visible at Mt Hamilton, and thus is a proper sampling for diffraction-limited wavefront sensing in the visible.

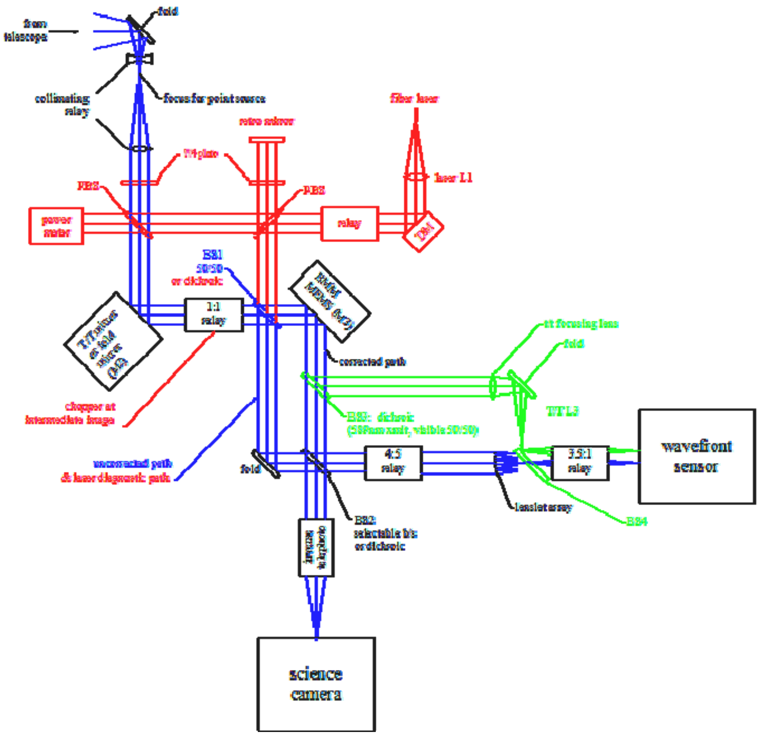

Figure 2. Optical layout of the Villages system. Blue indicates the path of the incoming starlight, starting from the telescope at upper left to the wavefront sensor and science camera to the lower right. Red indicates the path of the outgoing laser light for the phase 2 experiments, starting at the fiber feed at the upper right and going out the telescope at the upper left. The laser beam is to be inserted into the telescope beam path with a polarizing beam splitter (labled PBS in the figure).

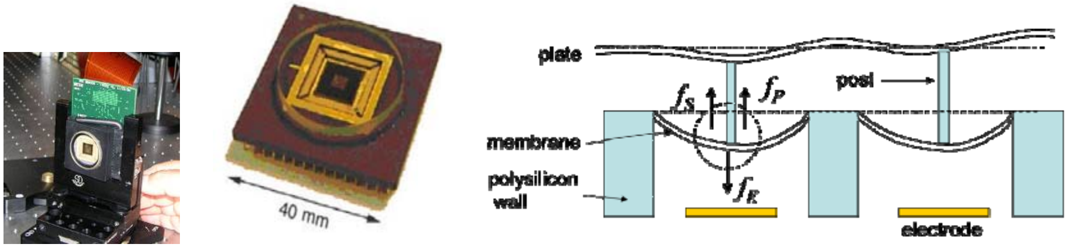

Figure 3. Left: 12x12 actuator MEMS deformable mirror shown in its connector package (courtesy Boston Micromachines Corporation). Right: schematic showing the mechanism of MEMS actuation. In each actuator, a static electric field pulls against the spring force of a membrane. The membrane is attached via a post to the reflectively coated face plate, producing a continuous face-sheet deformable mirror.

Wavefront Sensing and Control Method and Results

The deflections of position of the Hartmann spots on the assigned CCD geometry indicate the local slopes of the wavefront. Starting from raw camera frames, a real-time computer determines these slopes and reconstructs the continuous wavefront that is consistent with them. The Villages real-time controller is a dual Zeon processor that runs under the RT-Linux operating system. This processor is almost fully utilized when running this 144 actuator AO system at frame rates necessary for visible wavelength correction (1kHz). Obviously a larger aperture system (with control degrees of freedom scaling with D^2) will require a drastically different computer architecture. We have proposed a massively parallel architecture for future generation multi-laser guidestar systems.[4] Variants of this architecture are being designed for the TMT NFIRAOS system[5] and for the Keck Next Generation Adaptive Optics system.[6]

The closed-loop AO control scheme is the traditional integral feedback control mechanism where the residual post-DM wavefront is used as an incremental correction to the DM under the objective of driving the residual to a null. In open-loop the situation is different. First of all, the wavefront must be sensed accurately over a large dynamic range of full atmospheric wavefronts, since it is not operating around a null. Secondly, the non-linear and cross-coupled actuator response of the deformable mirror must be accurately modeled and accounted for in its drive signal.

For open-loop wavefront sensing, we use the entire 4x4 pixel sub-grid and center-of-mass algorithm to determine the spot deflection to high accuracy. With proper design of pixel scale, this is a very linear method of sensing over the full range of deflections and it was successfully demonstrated in the on-sky open-loop experiments.[7] Closed-loop wavefront sensing can utilize a quad-cell algorithm (using the central 2x2 grid) since it is null-seeking, but this was experimentally determined on-sky to not be sufficiently linear for open-loop sensing.

The open-loop control of the MEMS DM is based on the methods developed at the Laboratory for Adaptive Optics, which incorporate a linear plate equation model for the face sheet deflection as a function of actuator forces and empirically determined non-linear models for the actuator forces as a function of applied voltages.[8,9] This method proved remarkably accurate in laboratory tests (15 nm surface residual), and on-sky the open-loop control performance is consistent with this (see below).

On-sky Performance Results

The first on-sky closed loop experiments with bright natural guide stars were performed in November 2007. In this run we were able to achieve up to 25% Strehl ratio at 900 nm imaging wavelength (169 nm rms residual wavefront error). The image and chart in Figure 4 show some of the Strehl performance results. Our ultimate 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, v_{wind} = 5 m/s) seeing conditions. The MEMS device worked flawlessly and met our Experiment 1 goals of demonstrating MEMS suitability and robustness for astronomical AO in observatory conditions.

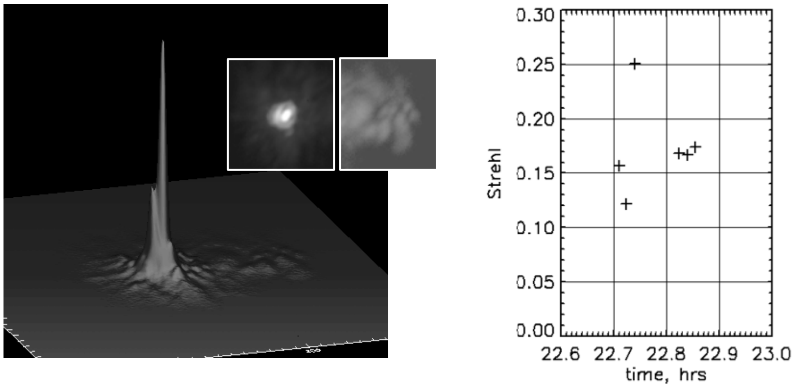

Figure 4. Left: Simultaneous images of DM corrected and uncorrected star α-Ari in I band (λ=0.9 μm) from observations on 11/21/07. Surface plot is linear scale. Inset images are log-stretched grey scale, with the corrected image on the left and the simultaneous uncorrected image on the right. Right: Strehl ratio over several short exposure (50 msec) images of α-Ari in I band.

The first on-sky open loop control tests were performed in early 2008. Figure 5 shows star images and error budget performance summary. The system achieved the diffraction limit in I (800 nm) and R (650 nm) bands, but not in V (550 nm), although in V the stelar image point-spread function was tighter and rounder than open seeing and had a full width half max of a little less than one half arcsecond.

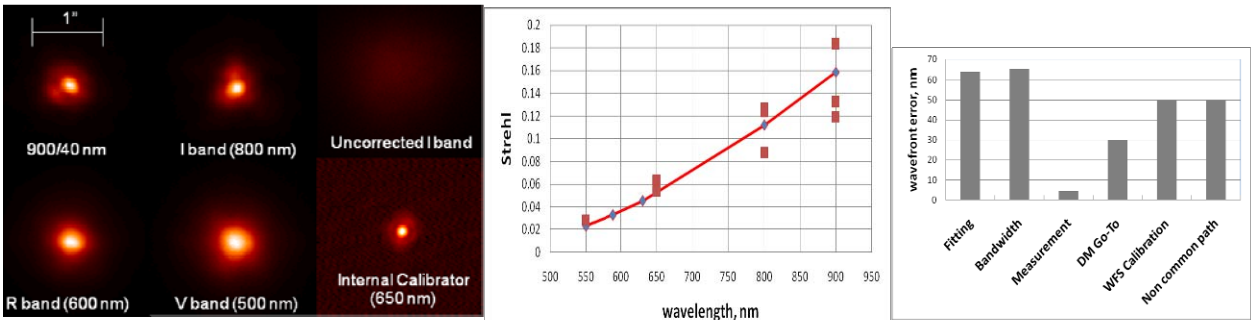

Figure 5. Left: Star images with open-loop control, from observations on 4/16/08. Middle: Measured Strehls and an error budget model fit. Right: Error budget allocation that it is consistent with independent measurements of r_0=7cm, wind=14m/s, and internal errors. DM go-to error was measured in an interferometer to 15 nm surface. WFS calibration error is based on wave-optic simulation and analysis of our wavefront sensor, and non-common path error is determined by measuring the Strehl on an internal diffraction-limited reference source.

Considerable telemetry data is available from the real-time system. This data includes WFS camera frames, computed Hartmann centroids, reconstructed wavefronts, DM mirror voltages, tip/tilt sensor readings, and tip/tilt mirror commands. Analysis of this data allows us to characterize compare the open and closed loop performance of the AO controller vs both spatial and temporal frequency.

Figure 6 shows the temporal frequency content of wavefront residuals for closed and open loop control cases. As expected, the open-loop control has higher temporal bandwidth (about 200 Hz, compared to 30 Hz, at 750 Hz frame rate) due to the fact that the controller provides the whole correction each time the wavefront is measured, whereas the closed loop control provides only an increment in the direction of null at each measurement. At low temporal frequencies however, the open-loop control does not decrease the wavefront error as well as in closed loop because the repeated refinements in closed loop continue to drive the DM toward a null wavefront reading, whereas in open loop the model for single-step actuation limits the accuracy. The recorded open-loop residual at low frequencies (representing about 2% error in correcting the wavefront) is consistent with the 15 nm surface accuracy in the open-loop control model of the MEMS device measured in the laboratory earlier.

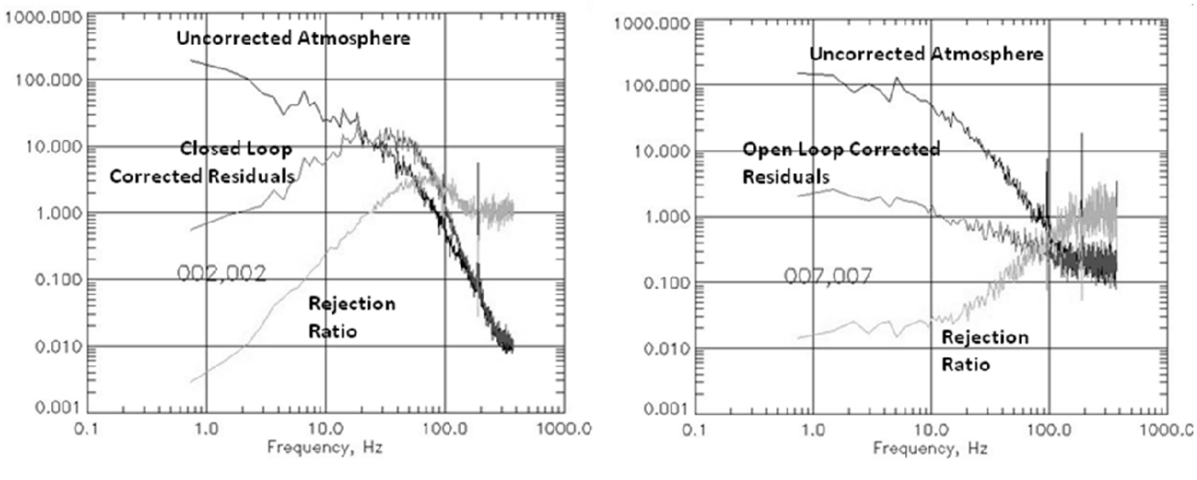

Figure 6. Temporal power spectra of rms reconstructed wavefronts, representing 1.4 seconds of 750 Hz data from the wavefront sensors. The left panel shows the closed loop control spectra and the right panel shows the open loop control spectra. Lighter curves are the ratio of corrected to uncorrected spectra, exhibiting the characteristic controller rejection behavior described in the text.

By monitoring the change in the low frequency rejection ratio of open loop control over the course of the year, we can monitor any drifts in our calibration of the open loop model. We continue to use the same DM open loop control model (a combination of linear plate equation theory with empirical nonlinear actuator fits) determined in the lab with an interferometer almost a year ago. So far we have seen perhaps a slight drift, up to closer to 5-6% error, but since this can be due to a number of systematic error sources including alignment it is currently work in progress to determine whether this is significant.

References

[1] Olivier, Scot S.; Max, Claire E.; Gavel, Donald T.; Brase, James M., "Tip-tilt compensation - Resolution limits for ground-based telescopes using laser guide star adaptive optics," Astrophysical Journal, Part 1 (ISSN 0004-637X), vol. 407, no. 1, p. 428-439 (1993).

[2] Gavel, Donald; Ammons, Mark; Bauman, Brian; Dillon, Daren; Gates, Elinor; Grigsby, Bryant; Johnson, Jess; Lockwood, Chris; Morzinski, Kathleen; Palmer, David; Reinig, Marc; Severson, Scott, "Visible light laser guidestar experimental system (Villages): on-sky tests of new technologies for visible wavelength all-sky coverage adaptive optics systems," Proceedings of the SPIE, Volume 7015, pp. 70150G-70150G-11 (2008).

[3] Grigsby, Bryant; Lockwood, Chris; Baumann, Brian; Gavel, Don; Johnson, Jess; Ammons, S. Mark; Dillon, Daren; Morzinski, Katie; Reinig, Marc; Palmer, Dave; Severson, Scott; Gates, Elinor, "ViLLaGEs: opto-mechanical design of an on-sky visible-light MEMS-based AO system," Proceedings of the SPIE, Volume 7018, pp. 701841-701841-12 (2008).

[4] Gavel, Donald; Reinig, Marc; Cabrera, Carlos, "Fast hardware implementation of tomography for multi-guidestar adaptive optics," Proceedings of the SPIE, Volume 5903, pp. 138-147 (2005).

[5] Boyer, C.; Gilles, L.; Ellerbroek, B.; Herriot, G.; Véran, J. P., "Update on the TMT adaptive optics real time controller," Proceedings of the SPIE, Volume 7015, pp. 701531-701531-13 (2008).

[6] Gavel, Donald; Dekany, Richard; Max, Claire; Wizinowich, Peter; Adkins, Sean; Bauman, Brian; Bell, Jim; Johansson, Erik; Kupke, Renate; Lockwood, Chris; Moore, Anna; Neyman, Chris; Reinig, Marc; Velur, Viswa, "Concept for the Keck Next Generation Adaptive Optics system," Proceedings of the SPIE, Volume 7015, pp. 701567-701567-12 (2008).

[7] Ammons, S. Mark; Gavel, Donald T.; Dillon, Daren R.; Reinig, Marco; Grigsby, Bryant; Morzinski, Katie M., "Application of Hartmann linear calibrations to ViLLaGEs," Proceedings of the SPIE, Volume 7015, pp. 701546-701546-8 (2008).

[8] Morzinski, Katie M.; Gavel, Donald T.; Norton, Andrew P.; Dillon, Daren R.; Reinig, Marco R., "Characterizing MEMS deformable mirrors for open-loop operation: high-resolution measurements of thin-plate behavior," Proceedings of the SPIE, Volume 6888, pp. 68880S-68880S-12 (2008).

[9] Morzinski, Katie M.; Harpsøe, Kennet B. W.; Gavel, Don T.; Ammons, S. Mark, "The open-loop control of MEMS: modeling and experimental results," Proceedings of the SPIE, Volume 6467, pp. 64670G (2007).