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Hobby-Eberly Telescope Segment Alignment Maintenance System

Mark T. Adams*[a], Povilas Palunas[b], John A. Booth[b], James R. Fowler[a], Marsha Wolf[b],
Greg Ames[c], John Rakoczy[d], E.E. Montgomery[d]

[a]University of Texas - McDonald Observatory, Fort Davis, TX
[b]University of Texas - McDonald Observatory, Austin, TX
[c]Blue Line Engineering Co., Colorado Springs, CO
[d]NASA - Marshall Space Flight Center, Huntsville, AL

ABSTRACT

A sensing and control system for maintaining the optical alignment of the ninety-one 1-meter diameter hexagonal segments forming the Hobby-Eberly Telescope (HET) primary mirror array has been developed by NASA - Marshall Space Flight Center (Huntsville, AL) and Blue Line Engineering (Colorado Springs, CO) and implemented. This Segment Alignment Maintenance System (SAMS) employs 480 edge sensors to measure the relative shear motion between each segment edge pair and compute individual segment tip, tilt and piston position errors. Error information is sent to the HET primary mirror control system, which then corrects the physical position of each segment every 90 seconds. On-site installation of the SAMS sensors, ancillary electronics and software was completed in September 2001. Since that time, SAMS has undergone engineering testing. The system has operated almost nightly, improving HET's overall operational capability and image quality performance. SAMS has not yet, however, demonstrated performance at the specified levels for tip, tilt, piston and Global Radius of Curvature (GRoC) maintenance. Additional systems development and *in situ* calibration are expected to bring SAMS to completion and improved operation performance by the end of this year.

Keywords: Segmented mirror, Hobby-Eberly Telescope, alignment maintenance, edge sensors

1. INTRODUCTION

The Hobby-Eberly Telescope (HET) is a 9.2-m fixed elevation astronomical telescope with a segmented primary mirror. Located at the University of Texas at Austin - McDonald Observatory site in the Davis Mountains of far west Texas, the HET sits atop Mount Fowlkes at an elevation of 2,008 meters. The summit's meteorological characteristics and 1.0 arcsecond median FWHM site seeing[1] are well-suited to HET's performance and scientific niches. Descriptions of the telescope[2], its operational characteristics[2,3,4,5,6], scientific instrumentation[7,8,9] and science output[10,11] may be found at the indicated references.

The HET was funded and built by a consortium of five universities: the University of Texas at Austin, the Pennsylvania State University, Ludwig-Maxmilians Universität München, Georg-August-Universität Göttingen, and Stanford University. HET incorporates several features that are unique among the current generation of 8 - 10 meter class instruments, such as an Arecibo-like focal surface tracker. The HET's low cost design employs a spherical primary mirror of 91-segments supported by a steel truss. The primary mirror has a constant zenith angle of 35 degrees and remains stationary during an observation. Between observations, the primary mirror can be rotated and repositioned in azimuth to access different parts of the sky. Astronomical object images are acquired and followed across the mirror array at prime focus using a sophisticated tracking device located atop the telescope structure.

This paper reviews the motivation for the Segment Alignment Maintenance System (SAMS) and reports on the system's implementation and recent performance at the HET. Alignment techniques for the HET primary mirror are described in Section 2. HET primary mirror alignment maintenance and the SAMS development are reviewed in Section 3. An overview of the SAMS architecture is given in Section 4. A detailed discussion of SAMS performance at the HET, as of

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mid-summer 2002, is reviewed in Section 5. The McDonald Observatory's plans for further SAMS development and calibration are described in Section 6.

2. HET PRIMARY MIRROR ALIGNMENT

Development of robust, fast, high performance, operator-friendly algorithms for HET primary mirror alignment has been a task of considerable importance and priority. The telescope's optical error budget requires each segment to be aligned in tip and tilt to within 0.06 arcseconds r.m.s. and pistoned to within 0.3 mm of a master sphere of radius 26,163.9 mm.

The initial HET tip - tilt - piston alignment concept employed a Center-of-Curvature-Alignment-Sensor (CCAS), a dual arm polarization shearing Twyman-Green interferometer located at the primary's center-of-curvature (CoC).[19] The CCAS was developed by W.J. Schafer Associates, Inc. (Rome, New York). This instrument was delivered early in the HET construction phase, well before commissioning began, prior to the installation of a significant number of primary mirror segments. Unfortunately, the company disbanded before they could perform CCAS instrument integration, verification and test (IV&T) with more than seven segments.

Once the HET primary mirror array was well-populated with segments, a team of McDonald Observatory Austin and West Texas technical staff undertook an extensive engineering IV&T program to determine whether the CCAS instrument could function as the HET primary mirror alignment tool. This program demonstrated that the CCAS instrument could function for tip - tilt primary mirror alignment, but only for a subset of the 91 HET primary segments. The first phase of SAMS testing at the HET involved edge sensors deployed on just seven HET segments, for example, and the CCAS instrument was used successfully as a verification tool throughout this proof-of-concept exercise. In relatively benign environmental conditions, the CCAS improved the tip-tilt alignment on as many as 23 HET segments, but it could not align all 91 HET segments. The CCAS instrument functioned only on nights with shallow temperature gradients (less than 0.5 deg C / hour) and wind speeds and directions that produced optimal dome flushing (10 - 15 mph). Overall, the McDonald IV&T effort demonstrated that the CCAS interferometer produced fringes of inadequate visibility and had insufficient dynamic range to tip - tilt align all 91 primary mirror array segments. Piston alignment of mirror segments with the CCAS was never successful. The CCAS instrument functioned as expected for tip - tilt alignment over small segmented arrays, but it could not routinely and robustly function across HET's entire 10 m x 11 m aperture.

Since the CCAS interferometer performance was inadequate, HET operations personnel implemented a burst-antiburst stacking technique, an adaptation of an alignment technique first used at the Multiple Mirror Telescope (MMT). In the HET implementation, the CCAS interferometer's laser projector was used to illuminate the primary mirror from the CoC. Each mirror segment's return spot was viewed on a faceplate in the CoC tower. After identifying which spots were associated with which segments, half of the array's 91 segments were tilted such that their spots moved to the edge of the faceplate while the remaining half were aligned. The active segments were moved such that their returns formed a ring pattern, or “burst” out from the center into concentric rings. Software identified spots with specific mirrors. Once the mirror spots were identified with segments and their positions recorded, the mirrors were sent to the opposite sides of the rings, or “anti-burst.” The spots were re-identified and centroided. The mirrors were then moved so that each spot was sent to the center. After the first half of the primary mirror array was aligned, the procedure was repeated for the other half of the array. Then the spots were stacked on each other, hence the alignment process was called “stacking the mirror”. Since the segment actuators have some hysteresis, empirically determined corrections were added into the requested mirror motions during stacking.

In May 2001, since the a “burst-antiburst” stacking technique had failed to achieve the required accuracy, the decision was made to change the HET primary mirror alignment methods. Because of its widespread and successful use in similar applications, a Shack-Hartmann proof-of-concept instrument was devised to test new alignment techniques at HET. This system, the Mirror Alignment Recovery System Proof-of-Concept (MARS-POC) was installed in September 2001 in the CoC tower.[6]

The heart of MARS is the WaveScope, a commercial Shack-Hartmann wavefront sensor manufactured by Adaptive Optics Associates (Cambridge, Massachusetts). An expanding white light beam, originating through a fiber-fed pinhole at the CoC, is projected down to fill the primary. Each mirror segment in the HET array reflects a portion of this light back to a focus at the CoC, which is coincident with the back side of a beamsplitter cube in MARS. After the cube, a lens collimates the beam and images the HET mirror array onto a custom lenslet array, sized to match the HET image. Each hexagonal lens focuses the light from its mirror segment to form a grid of spots on a CCD camera inside the WaveScope. The CCD camera is on a translating stage to allow imaging of either the focused spots from the lenslets or the lenslet array itself, along with a HET primary mirror pupil image.

An internal reference beam is sent into the WaveScope for calibration. This beam consists of light reflected from a reference sphere that has its CoC at the same point as the HET. The lenslet array samples light from the reference mirror and each lens focuses spots whose grid locations correspond to those from a “perfect” sphere, analogous to a perfectly aligned segmented mirror. The HET spot positions on the CCD are compared to the reference spot positions. Differences in these positions, caused by misaligned mirror segments, measure segment tips and tilts. Corrections are then sent to the HET's Segment Positioning System, aligning the primary mirror array.

3. SEGMENT ALIGNMENT MAINTENANCE SYSTEM DEVELOPMENT

During testing of HET image quality during commissioning, composite star images from the individual mirror segments were observed to "de-stack" or wander with respect to one another. Though thermoelastic deformations in the steel support truss couple with nonlinearities in joints and interfaces were expected to cause measurable mirror segment misalignment on timescales of 1 - 2 hours, the observed "de-stack" was much larger than the anticipated sub-arcsecond segment motions. The observed CoC spot size was found to enlarge at a mean rate of 0.6 arcsec / hour in conditions where the nocturnal ambient temperature varied at a typical West Texas lapse rate of 0.5 deg C / hour. A set of engineering tests were designed and executed in August and September 1998 to determine whether these larger motions indicated problems with the individual segment mounts. These "solid mount" tests clearly indicated that the "de-stack" originated not in the segment mounts but in the steel primary mirror truss. [14]

To provide the required optical performance, a management decision was made in October 1998 to pursue the development and procurement of an alignment maintenance system for the HET's segmented primary mirror array.[12] The successful alignment maintenance system functioning on the segmented mirror Keck telescopes provided a worked example, though the HET's significantly different cost and operations regime precluded simply replicating Keck's solution for several reasons. The Keck telescopes had been designed with an alignment maintenance system from the beginning; HET's system was a retrofit. The Keck capacitative sensing paddles weigh ~ 1 kg. Keck segments were figured with this additional mass in mind. Similar paddles, if attached to the HET segments, would destroy the segment optical figure.

The HET Board of Directors recognized the need for a SAMS and authorized McDonald Observatory to proceed with its development in December 1998. Since a SAMS had not been part of the original HET vision, its capital cost had not been budgeted. A relatively inexpensive solution, costing less than $1M, was needed.

A Statement-of-Work and specifications for a HET Segment Alignment Maintenance System were completed in March 1999. These specifications called for a SAMS that maintained tip - tilt alignment and Global Radius of Curvature (GRoC) for a minimum of 14 days without external intervention. Piston was required to be accurate for a minimum of 90 days. The SAMS Request for Quotation was sent from the University of Texas Purchasing office on 7 June 1999. Several vendors responded and in August 1999, the SAMS proposal evaluation team selected the NASA - Marshall Space Flight Center / Blue Line Engineering proposal on the basis of technical excellence, completeness, and overall value. Thus, in November 1999, the University of Texas at Austin - McDonald Observatory entered into a Space Act Agreement with NASA’s Marshall Space Flight Center (MSFC) for the purpose of procuring a Segment Alignment Maintenance System (SAMS) for the HET. More than a year of continuous, high-level engineering and management effort was required from the time of decision to procure SAMS to a signed contract with a technically capable vendor.

For their SAMS proposal, MSFC teamed with Blue Line Engineering of Colorado Springs, Colorado. Blue Line provided the edge sensing system and electronics. MSFC developed control algorithms and control system software. MSFC also managed system integration and verification testing.

A proof-of-concept, Sub-Array Test (SAT) was performed at the HET with the MSFC - Blue Line Engineering SAMS edge sensor system in fall 2000. This SAT deployed edge sensors on seven adjacent HET segments. Use of the CCAS interferometer as the SAT verification tool proved problematic since the CCAS instrument functioned sufficiently well only in the best seeing conditions. Nonetheless, SAT did demonstrate the basic functionality of the edge sensor hardware and software systems. At the Critical Design Review (May 2001), the only substantial build change was the decision to manufacture the edge sensor brackets out of Invar™ rather than aluminum.

Installation of the SAMS hardware -- Invar attachment buttons and brackets, passive and active edge sensors, and ancillary electronics -- was accomplished in an expeditious manner by Blue Line Engineering personnel in August and September 2001 during an extended engineering period focussed on other HET improvements. The SAMS installation itself required minimal telescope downtime.

The SAMS edge sensor hardware and software became operational on the Hobby-Eberly Telescope on 13 October 2001. Installation of the GRoC estimator and the final software verification were completed in December 2001.

4. SEGMENT ALIGNMENT MAINTENANCE SYSTEM ARCHITECTURE

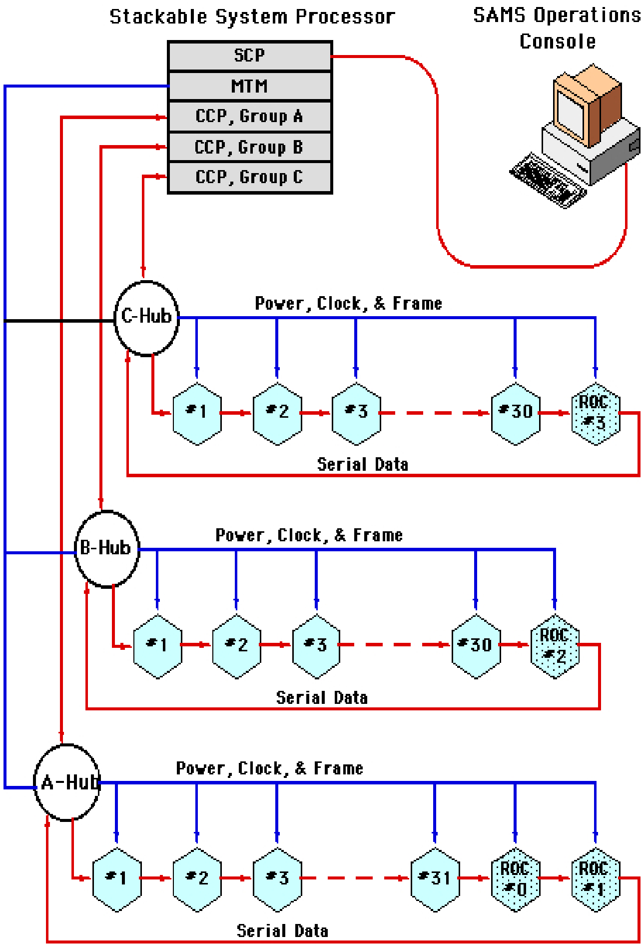

Figure 1 - System block diagram for SAMS. Power supply and SSP to be located in enclosure behind telescope truss. Console to be located in control room. All other system modules to be located on the truss.

The Keck telescope pioneered figure control of segmented telescope mirrors, demonstrating that an array of position sensors could be employed for this purpose[16,17]. Such position sensors are generally referred to as "edge sensors." SAMS is based on edge sensor technology developed at Blue Line Engineering Co. in conjunction with NASA - Marshall Space Flight Center. As implemented at HET, SAMS divides into two principal components: (1) the console, residing in the HET control room; and (2) the array of edge sensors, data acquisition and signal processing electronics located in the HET dome, near and behind the primary mirror array. Figure-1 is a system block diagram for SAMS.

A distributed, modular processing system was developed by Blue Line Engineering and implemented to meet the challenges posed by the requirement for closed-loop control of 91 HET segments. The executive level processor, or console, is at the top of the SAMS architecture. The console includes a graphical user interface (GUI) for interactions between the HET Telescope Operator and SAMS. The console permits control of fundamental system operations, plus diagnostic and data analysis tools. A single serial data link connects the console to the stackable system processor (SSP), a small, modular parallel processor.

The System Control Processor (SCP) is the interface between the sensor and data analysis components of SAMS. The SCP is a single-board computer (Motorola 68332 processor). It reduces the complexity of controlling and operating the system. All sensor to console communications are handled by the SCP. The SCP coordinates the operation of a bank of parallel DSP-based modules, the Cluster Control Processors (CCPs), and other auxiliary modules connected to a stackable parallel data bus. The SCP also handles telemetry extraction, general health and status monitoring, downloading and initialization, and master timing control.

Each CCP is a high-speed, dedicated processing unit for handling groups or functionally divides the 91 segment HET primary mirror array into three clusters. The digital signal processor for the CCP module is the Motorola 56301, a 24-bit processor capable of 80M arithmetic operations per second. To permit full duplex interprocessor communication at 22 MHz, each CCP is connected to two serial data busses (A and B). Four of the Motorola 56301's seven DMA channels may be used for inter-processor communication.

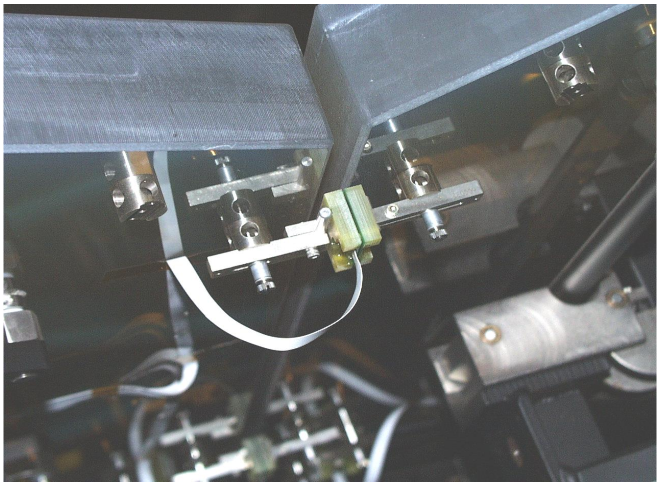

Figure 2 - Active (left) and passive (right) edge sensors installed between two HET mirror segments

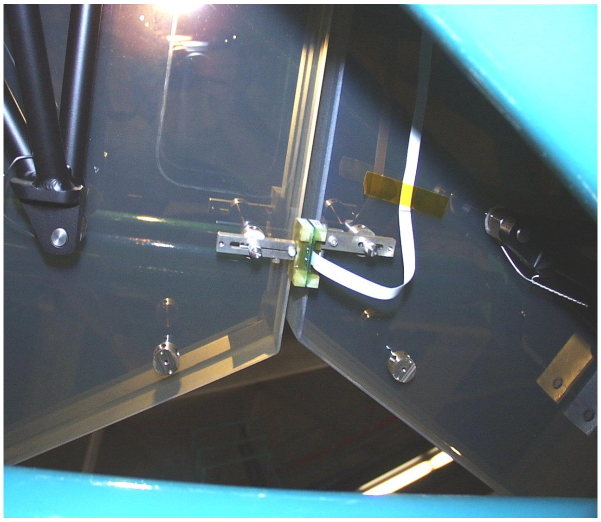

Figure 3 - A rear view of an active - passive edge sensor pair installed between two HET mirror segments

The SAMS Master Timing Module (MTM) outputs the timing signals, including a 4 MHz master clock and a frame sync that sets the SAMS sample rate.

The system Hubs serve as the main branching point in the distribution harness for power and timing signals. The Hubs also play an important role in the transmission and reception of data to and from the individual segments, and can aid in system troubleshooting. Data handling is performed by a circuit board dubbed the "cluster data router - concentrator" (CDRC). This board receives the high speed serial data stream from the CCP via fiber optic and synchronizes the transmission of data through a segment electronics daisy chain.

Nodes occupy the lowest system architecture level. Each is composed of a DSP board that processes sensor data. This board also sends and receives data via the serial link to its group control processor. Each node contains edge sensor electronics and analog-to-digital converters. Each node contains the edge sensors electronics and analog-to-digital-convertors to support the sensors on a single segment

The 480 inductive edge sensors are the heart of SAMS. Their 50 nm resolution and substantial dynamic range are critical to SAMS performance. As developed by Blue Line Engineering, these edge sensors are insensitive to dust, condensation, relative humidity, and dielectric changes. Each sensor head assembly is lightweight, weighing less than 50 gm. Two pairs of inductive coils are located on the opposing faces of adjoining HET optical segments, which are separated by a 6 to 25 mm gap. Each coil pair consists of an active, powered coil and a passive, unpowered coil.

The two active sensing elements form an RLC network, driven by a frequency-stabilized source and inductively coupled to the two passive coils, which are connected to form passive LC networks. Any relative motion of the adjacent optical segment edges causes a change in the complex impedance of the active coils. This impedance change is detected with a synchronous demodulator. The output voltage is linearly related to the relative motion, or edge match error, between segment edges. The shear values are sent to the system console once per second for further processing.

The console level control system converts sensor, gap and temperature data to tip, tilt, and piston. It also functions as a local monitoring and debugging interface. It employs a network-based remote command interface, and has network connectivity for connection to the existing mirror control system. GRoC is calculated here, based on measurements of gap and temperature.[11,15] This control system also provides the ability to select and deselect sensor inputs, segment tip/tilt/piston outputs and controls calibration routines.

5. SEGMENT ALIGNMENT MAINTENANCE SYSTEM PERFORMANCE

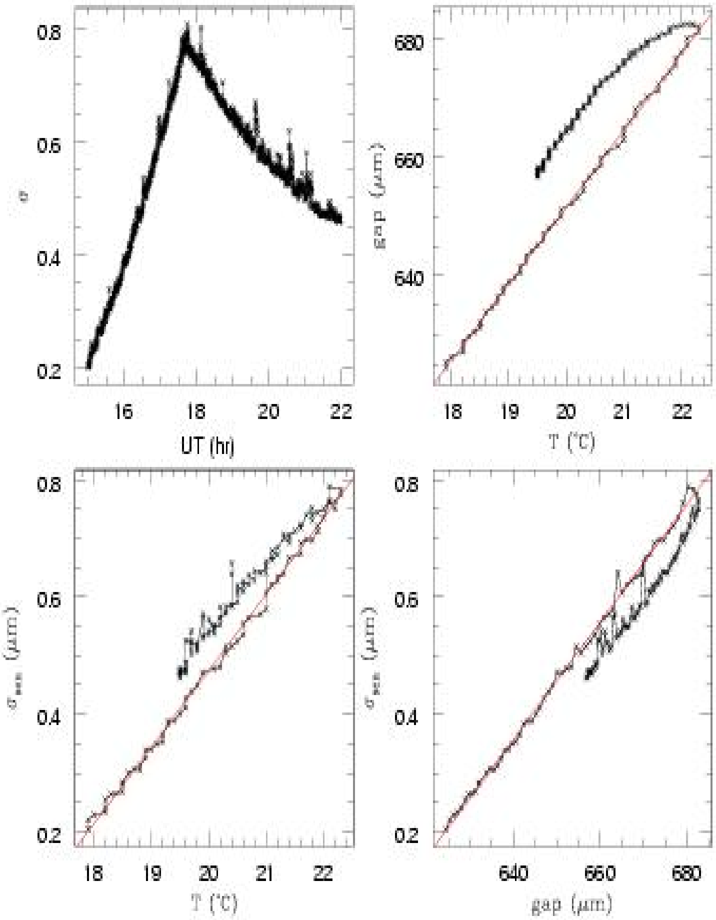

Figure 4 - The upper left panel shows the time evolution of the rms SAMS edge sensor deviation from a reference. The upper right panel shows the average gap between the sensors as a function of temperature. The lower left and lower right panels illustrate the rms edge sensor deviation as a function of temperature and gap, respectively.

SAMS has been an integral part of HET night-time operations since October 2001. As expected, it has improved the telescope's image quality performance and operational efficiency, though additional performance gains are required and expected.

Currently, the median HET image quality, immediately after restacking the primary mirror array with the Mirror Alignment Recovery System, is 0.9 arcsec (EE50), as measured with a resolved source at the CoC. With SAMS, the HET median image quality typically degrades from 0.9 arcsec (EE50) to 1.3 arcsec (EE50) over 3.6 hours, a mean degradation rate of ~ 0.1 arcsec / hour. This is a six-fold improvement of the image quality degradation rate observed at HET prior to the installation of SAMS, but does not meet the system specification. On-going HET - SAMS characterization and calibration efforts have, as their ultimate goal, the reduction of this primary mirror degradation rate by at least another factor of five and, preferably, an order of magnitude.

Prior to SAMS, primary mirror alignment was typically required once every 60 minutes to recover image quality and consumed 25 - 30% of the available night-time operations hours. Since SAMS became operational, the median time between stacks has increased from 1.0 to 3.6 hours, with a corresponding decrease in the fraction of night-time operations devoted to primary mirror alignment and an increase in the time available for science. The primary mirror array is now typically re-stacked twice per night.

Though SAMS has improved image quality and operability, it has not yet performed to acceptable specifications. The two principal limitations of SAMS are its temperature-sensitivity and incomplete calibration.

The SAMS specification required that the system maintain primary mirror alignment over an ambient temperature range of at least 10 deg C. If SAMS performed in accord with this temperature range requirement, no more than one primary mirror stack would be required per HET operations night and SAMS would often provide alignment maintenance across multiple nights. As currently implemented, SAMS operability is limited to a range of no more than 1.5 deg C. [18] Once the ambient temperature has departed 1.5 deg C or more from the temperature at the time of the last primary mirror alignment, SAMS alignment errors become a significant factor in the current performance of the telescope, and the primary mirror array must be re-aligned.

This ambient temperature-sensitivity originates with the edge sensors and edge sensor electronics. Blue Line Engineering has developed a software-based temperature compensation algorithm for the edge sensor system, but its implementation at HET has not yet demonstrated any significant performance improvement. Figure-4 quantifies these temperature-dependent effects. During this engineering test, the dome temperature was intentionally allowed to rise throughout the day, until 17:35 UT. The air conditioning system was then turned on. The upper right panel shows the average gap between the sensors as a function of temperature. A least squares fit of these data implies a coefficient of thermal expansion (CTE) of 13 ppm / deg C; the steel truss CTE is 10.5 ppm / deg C. Note that the trajectory for decreasing temperature in this panel indicates ~ 13 μm / meter of backlash in the steel primary mirror truss. The lower left and lower right panels show the rms sensor deviation as a function of temperature and gap, respectively. Engineering efforts are continuing to understand and characterize this temperature compensation problem.

Completion of the *in situ* calibration of the SAMS edge sensors is a priority. The system's current implementation uses theoretical calibration coefficients. Recent engineering testing has demonstrated that the implemented theoretical sensor gains are significantly different from those derived from *in situ* calibration. In open loop mode, the r.m.s. precision of a typical edge sensor is 15 nm. In closed loop mode, however, the r.m.s. precision of the system degrades to 130 nm owing to actuator error and the implementation of differences between the theoretical and actual sensor gains. The system also shows evidence of limit cycles due to gain errors.

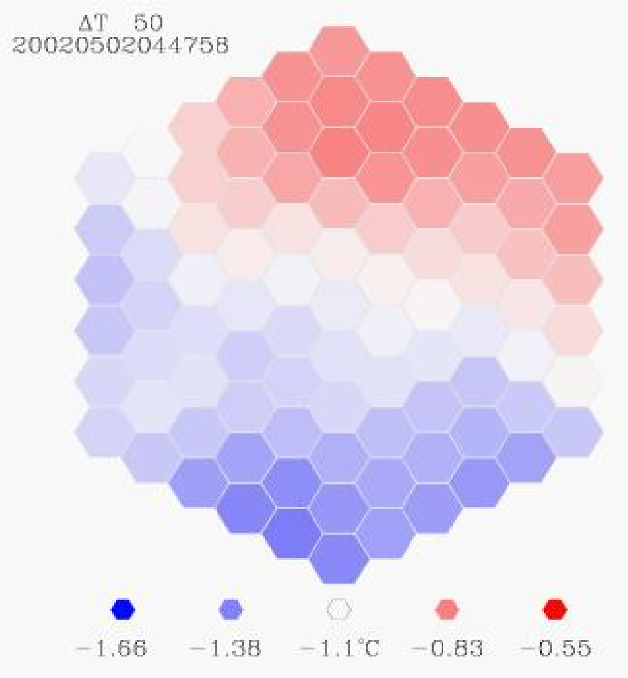

Figure 5 - Edge sensor temperature variation over the HET primary mirror array during 75 minutes on 2 April 2002.

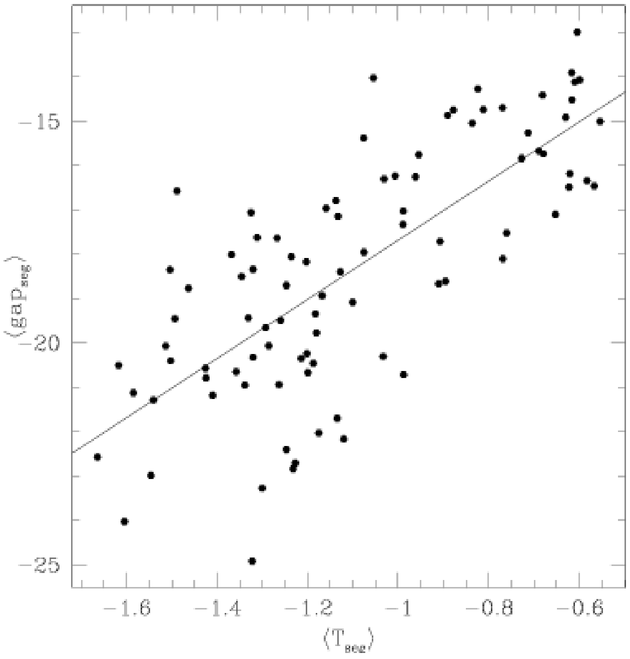

Figure 6 - Mean edge sensor gap change versus temperature change for the data shown in Figure 5.

Small non-uniformities in the dome cooling and temperature stratification can yield thermal gradients across the 10 x 11 m primary mirror truss of ~ 1 deg C (Figure-5), as measured at the SAMS temperature sensors. Although there is a thermal lag between the primary mirror truss and the edge sensors, the SAMS temperature sensor measurements correlate well with the gap measurements, as shown in Figure-6. These temperature gradients lead to modes which are not sensed by SAMS. Simulations indicate that these temperature gradients can cause figure errors that may add up to 0.4 arcsec (EE50) in quadrature to the HET optical error budget. Operations procedures are being implemented to minimize these temperature gradients. These errors exceed the SAMS specifications, but are not currently the dominant errors affecting perfomance.

Over the coming year, McDonald Observatory engineering characterization and calibration efforts are expected to improve SAMS performance to at or near specification levels. The current performance of SAMS is such that HET CoC image quality degrades from 0.9 to 1.3 arcsec (EE50) over a period of 3.6 hours, the typical time for an ambient temperature variation of 1.5 deg C. The Observatory's goal is for SAMS to maintain the alignment of the primary mirror array such that the HET image quality degrades by no more than 10% when the temperature gradient from 12 deg evening twilight to 12 morning twilight is < 6 deg C, a condition that is met on 90% of the spectroscopic and photometric nights in West Texas.

6. SUMMARY

A Segment Alignment Maintenance System (SAMS) has been implemented for the Hobby-Eberly Telescope's segmented primary mirror array. SAMS was developed by NASA - Marshall Space Flight Center in collaboration with Blue Line Engineer, Co. The implemented SAMS employs a closed-loop edge sensor system.

Since its installation at HET in fall 2001, SAMS has improved HET's image quality performance and substantially reduced the amount of time required each night for re-stacking the primary mirror array. Over the next year, implementation of edge sensor temperature compensation and improved calibration is expected to bring SAMS to its specified performance level.

7. ACKNOWLEDGEMENTS

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*Mark T. Adams, mta@astro.as.utexas.edu, phone: 1-915-426-3263, Fax: 1-915-426-3641, University of Texas at Austin - McDonald Observatory, HC 75, Box 1337-MCD, Fort Davis, TX 79734-5020