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Control of the Hobby-Eberly Telescope Primary Mirror Array with the Segment Alignment Maintenance System[*]

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ABSTRACT

The Segment Alignment Maintenance System (SAMS) is a control system to maintain the alignment of the 91 segment Hobby-Eberly Telescope (HET) primary mirror array. The system was developed by Blue-Line Engineering (Colorado Springs, CO) and NASA-Marshall Space Flight Center (Huntsville-Al). The core of the system is a set of 480 inductive edge sensors which measure relative shear between adjacent segments. The relative shear is used to calculate segment tip/tilt and piston corrections. Although the system has dramatically improved the performance of the HET it does not meet its error budget due to thermal drifts in the sensors. The system is now sufficiently stable that it routinely requires only one primary mirror alignment at the beginning of the night. We describe methods to calibrate this sensor drift.

Keywords: Hobby-Eberly Telescope, HET, SAMS, edge sensors, control systems

1. INTRODUCTION

The Hobby-Eberly Telescope (HET)[1] is a fixed elevation telescope with an 11m primary mirror array consisting of 91 closely packed hexagonal segments. The HET design employs an Arecibo-style spherical primary and focal surface robot which tracks objects in the sky. The final image is formed by a 4-mirror double-Gregorian spherical aberration corrector which rides in the tracker robot. The primary, which is tilted 35° from zenith, remains stationary during observations. Between observations the telescope can be rotated in azimuth to access different regions of the sky. The HET is a special purpose telescope designed for spectroscopic surveys. Its unique design allowed the telescope to be built for a construction cost of only $13.9 M about 15% of the cost of a fully-steerable telescope of comparable size. The telescope was funded and built by the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München, and Georg-August-Universität, Göttingen..

The HET is the prototype for extremely cost-effective large telescopes. Cost-savings measures were pushed to the extreme and the telescope fell short of specifications[1,2]. In early operations the typical delivered image quality was 2.5-3.0 arcsec FWHM and observing efficiency was poor. A concentrated effort with additional manpower and funding was launched to understand and address these problems[3,4]. Two of the most significant contributors to the poor performance were the primary mirror and the tracker robot. Both of these critical and highly complex opto-mechanical systems were being run open loop and could not maintain specified alignment tolerances.

The alignment of the 91 segments in the primary mirror array degraded significantly on timescales of under an hour due to thermally driven deformations in the underlying bolted steel support truss. To correct this shortfall an edge sensor system, the Segment Alignment Maintenance System (SAMS) was procured to close the loop on the primary mirror control system[5]. SAMS was contracted to NASA Marshall Space Flight Center and Blue Line Engineering in November

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[*] The Hobby-Eberly Telescope is operated by McDonald Observatory on behalf of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München, and Georg-August-Universität, Göttingen

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1999. The system went into operation starting in January 2002[6,7]. The system provided an immediate improvement to HET operations by reducing the number of required array realignments, or stacks, of the primary to just 2 or 3 per night. Additional improvements were expected after calibration of the sensors for thermally driven systematic drifts. However, early attempts to calibrate the sensors were not successful[7].

In this paper we describe continuing efforts to calibrate the SAMS sensors.

2. BACKGROUND

2.1. Primary Mirror Array

Figure 1. HET Primary mirror array and truss

The HET primary mirror array consists of 91, 1 m (flat-to-flat) , hexagonal segments . The array spans 11.1 m point-to-point and 9.8 m flat-to-flat. It is supported by a three-layer truss fabricated from steel tubing 50-100 mm in diameter bolted to spherical steal nodes 100-200 mm in diameter. The truss is supported by the telescope structure in a kinematic mount at fixed angle of 35° from the zenith. The gravity load on the primary and its support structure is constant easing the requirements for maintaining the alignment of the array.

The segments are made of 50 mm thick blanks of Schott Zerodur. They are figured with a spherical surface of radius 26.164 m. Each segment is mounted on a steel frame and supported axially by nine points through three wiffletrees and radially through its center of mass by a flexure mounted hub. The tip, tilt and piston of a segment are controlled by a stepper-motor driven actuator through a compound lever system that provides 19.2 nm resolution. The smallest piston free tip is 0.013 arcsec and the smallest piston free tilt is 0.018 arcsec. The optical error budget requires each segment to be aligned in tip and tilt to within 0.06 arcsec RMS, or 0.14 arcsec FWHM.

2.2. Stacking the Array

The array is aligned, or stacked, periodically in tip and tilt with the mirror alignment recovery system (MARS)[8]. This system is located at the center of curvature (CoC) of the primary mirror in tower built next to the HET dome. MARS is built around a WaveScope: a commercial Shack-Hartman wavefront sensor manufactured by Adaptive Optics Associates. A custom hexagonal lenslet array is sized so that each lenslet matches a segment in the primary mirror. An internal reference beam can be sent into the WaveScope for calibration.

The stacks are evaluated by direct imaging at CoC with the Hartmann extra focal instrument (HEFI)[4]. HEFI is mounted to the MARS optical bench and consists of a camera, light source and retractable fold mirror. The average aligned array, or "stack", imaged at the CoC is 0.5-0.6 arcsec in size. Stacks as small as 0.4 arcsec have been recorded under exceptional dome seeing conditions. The average spot size for a single segment is about 0.4 arcsec. The alignment accuracy of the array is therefore between 0.2-0.4 arcsec.

The piston of the array is maintained by periodic measurement with a handheld spherometer. Relative segment-to-segment height differences are measured manually from the basket of a person lift. The piston alignment degrades about 30-40 μm RMS per month.

3. SAMS

SAMS is a feedback control system used to maintain the alignment of the HET primary mirror. SAMS consists of inductive edge sensors, sensor conditioning, communications electronics and a central control computer. The sensors are arrayed along the edges of the segments with two sensors per edge. There are a total of 480 sensors. Each segment has is own local electronics “hub” controlling up to 6 sensors. The 91 segments are divided into 3 groups or “nodes” of 30 or 31 sensors each. Each node is controlled by a cluster control processor (CCP). Control of the three CCPs is maintained by a master system control processor (SCP). The SCP provides the single point interface to all of the sensor and data acquisition component of SAMS. The SCP handles all communications with the operations console.

3.1. SAMS sensors

At the heart of the SAMS are the differential inductive edge sensors developed by Blue Line Engineering. The sensors provide measurements of the relative vertical displacement (or shear) and gap between the edges of two segments. Each SAMS sensor consists of an active and a passive RLC circuit mounted on the opposing edges of adjacent segments. The active side network is driven by a frequency stabilized source; the passive side is unpowered. Flat spiral wound coils on the active side couple inductively to identical coils on the passive side. The coefficient of coupling between the coils and hence the complex impedance of the network is a function of the relative position of the coils. The response of the network to the driving source gives a measure of the impedance and therefore relative position of the coils. The sensors have two channels or a total of four coils. A differential measurement of the impedance of the two channels provides a measurement of shear. The average impedance provides a measurement of gap.

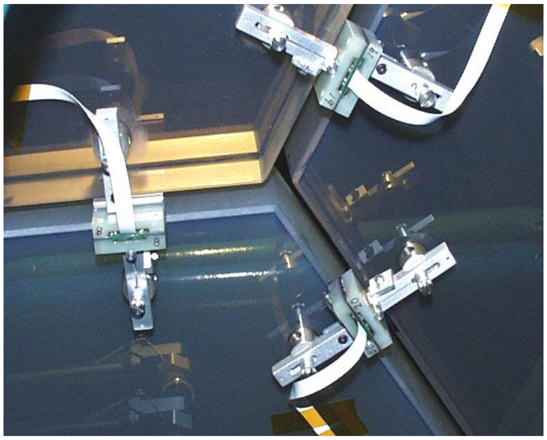

Figure 2- SAMS sensors installed at three segment edges

To the extent that each channel has the same response the differential nature of the shear measurement reduces errors due to common mode effects such as changes in gap or temperature. A major advantage of inductive sensors for use in telescopes is that they are insensitive to dielectric changes such as those due to dust, humidity or condensation which can be very difficult to control or compensate.

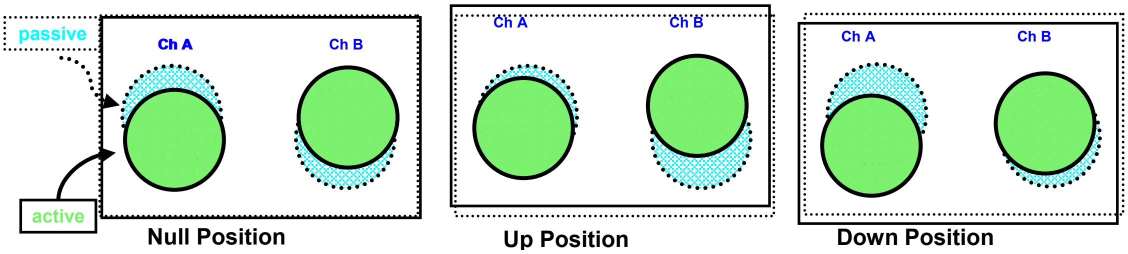

Figure 3. Sensor geometry for differential shear measurement

3.2. SAMS sensor systematics

Although the SAMS inductive sensors are insensitive to dielectric changes the RLC networks are sensitive to temperature changes and geometric errors. The system as installed on the HET was expected to need calibration for the following systematics: (1) nominal scale factor or gain (2) temperature dependence of the gain and (3) temperature dependent bias. The gain is a multiplicative sensor error and the bias is an additive sensor error. Every SAMS edge sensor has an onboard temperature sensor to make a local temperature measurements to correct for these effects. It has been subsequently found that the sensors also have a significant bias depending on the gap between the active and passive sides of the sensors. In operation the gap follows the temperature due to thermally driven expansion and contraction of the truss, however the thermal lag of the truss requires that the gap and temperature effects be treated separately. The SAMS sensors have an intrinsic noise of 15nm rms.

3.3. SAMS control

The SAMS sensors place 480 constraints on the 273 tip, tilt and piston degrees of freedom of the 91 segments in the primary mirror array. The system is over-constrained and the control law is derived by a least-squares psuedo-inverse solution of the influence function[9]. The influence function is a matrix equation giving the response of the sensors to changes in the tip, tilt and piston of the segments. The control system is a nulling system which drives the sensor errors, the values minus an initial reference, to a least-squares minimum. We use the RMS of the sensor errors at the least-squares minimum (denoted the Target RSE) as a metric of SAMS sensor performance. Due to systematic biases and noise of the sensors the Target RSE cannot be zero.

The control system responds to random sensor biases by moving the primary mirror array away from the initial alignment in order to minimize the Target RSE. Errors in the sensors lead to errors in the array alignment. Simulations of the SAMS control law show that a random distribution of sensor bias with 100 nm RMS leads to a Target RSE of 72nm and adds 0.33″ FWHM to the image quality error budget. The installed system showed a growth of 110 nm/°C in the Target RSE which added 0.5″ FWHM/°C in quadrature to the delivered image quality. At this time the typical delivered image quality of the telescope was 2.0-2.5 arcsec FWHM and most nights required at least 2 stacks of the primary mirror for temperature changes of ~1.5°C.

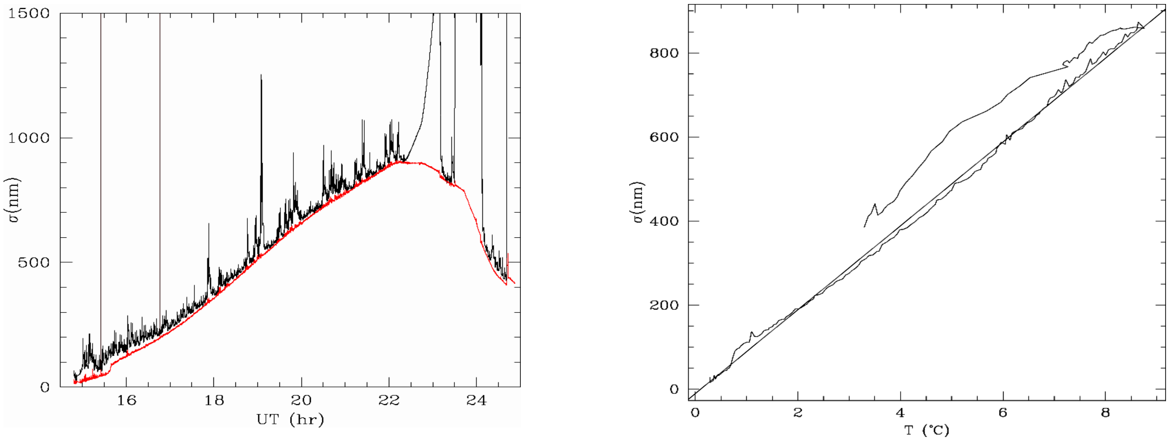

Figure 4. Target RSE as a function of time and temperature change during early operations of SAMS

4. SENSOR CALIBRATION

We have pursued two strategies for calibrating the SAMS sensors: direct independent characterization of individual sensors and in situ characterization of the sensors. Independent characterization of the sensors allows better control and separation of the sensor systematic. In situ measurement allows efficient measurements of all 480 sensors.

4.1. Thermal dependent Shear Bias/Sandwich Tests

To measure the thermal drift of the sensors we designed a fixture to sandwich the active and passive sides of a sensor at fixed shear and gap (Fig. 5). The fixture consisted of Delrin clamp and plastic shim material. A set of these fixtures was manufactured and installed on 30-40 sensors at a time distributed throughout the array. These sensors were removed from the control loop and SAMS remained operational during the test. The sensor values were logged as the ambient temperature in the dome varied over the course of several days.

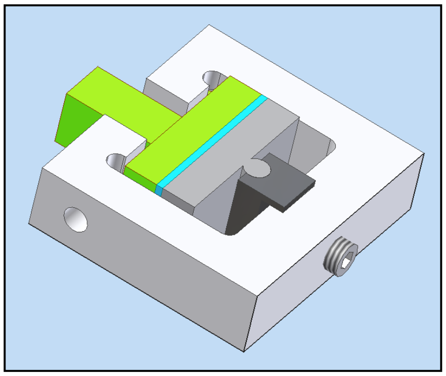

Figure 5. Sensor sandwich fixture for thermal bias tests.

The temperature dependent bias was measured for a total of 102 sensors and found to be 22±21nm/°C. The temperature dependent bias should add in quadrature to other systematic effects. The temperature dependent bias was determined to be insignificant compared to the observed growth of the Target RSE during normal operations.

4.2. Gap dependent Shear Bias/Stage Tests

We measured the response of the sensors changes in gap directly using a 3-axis flexure stage. Access only allowed a small number of sensors to be characterized by hand. Various biases in the measurements due to cross coupling of the stage axes were removed by making the measurements first with the active side of the sensor on the fixed platform of the stage and then with the passive side on the fixed platform. The stage errors remained the same in both cases while the sign of the sensor response to the stage errors was reversed. The average of the two measurements yields the true sensor response. The most significant stage error was arcuate motion due to the rotation about the stage flexures. This cross coupling caused motion along the shear direction as the stage was moved in the gap direction. The measured arcuate motion is consistent with the 27 mm design length of the flexures in the stage. Figure 3 shows an example of the measurement for on sensor. The residuals to a linear model fit have a 17 nm rms.

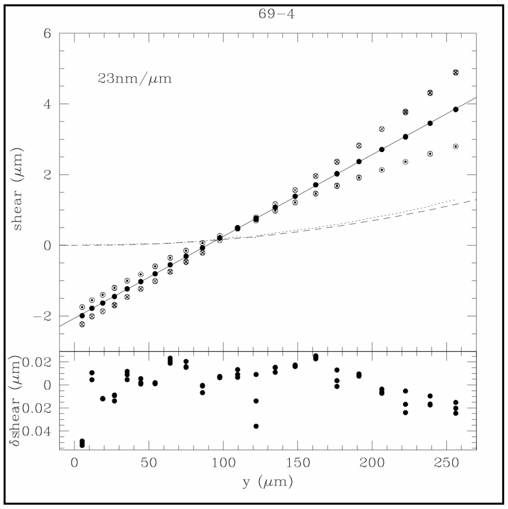

Figure 6. Shear as a function of changes in gap measured in the stage test.

The dependence of the measured shear to changes in gap was found to be 20-30 nm shear / µm gap for the measured sensors. This corresponds to 200-300 nm / °C for thermally driven expansion or contraction of the primary mirror truss. The gap therefore appears to be the primary bias driving the performance of SAMS.

4.3. In Situ Scale Factor Calibration

The scale factor, or gain, for the sensor shear was calibrated by measuring the shear while pistoning each segment in discrete steps. The calibration was done in three sets so that no neighboring segments move at the same time (Fig. 7). Each set was pistoned down by 75 µm followed by six upward piston steps of 25 µm each. The total range of motion for the tests was 125 µm. To avoid problems with backlash the data from the initial downward step and the first upward step was ignored in the analysis. A linear-least-squares fit to the remaining data yielded the gain. Each sensor has two independent measurements of the gain; one while moving the active side segment and one while moving the passive side segment. The test was done many times at different temperatures to measure thermal effects. The temperature range spanned by the tests was 20°C. The repeat measurements of the scale agree to 1% RMS and the independent measurements agree to 4% RMS.

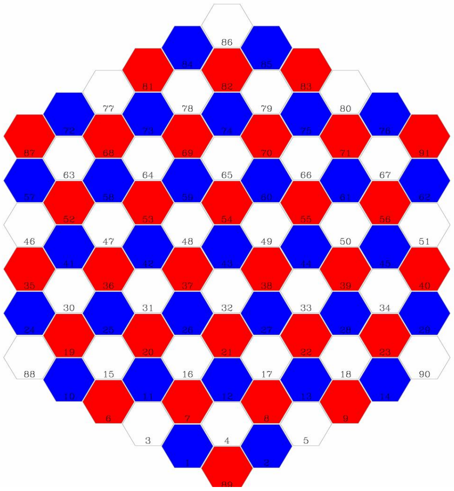

Figure 7. Pistoning pattern for sensor gain measurements

The independent measurements provide a statistical measurement of the accuracy of the positioning accuracy of the segment mounts. The average temperature dependence of the sensor gain is 0.0006°C^{-1}. The sensors are normally operated near their null point where the gain systematics are minimized. Typically the sensors are set and maintained to with 10-30 µm RMS. Because of this the temperature dependence of the scale factor for the sensors has thus far been a minimal contributor to the degradation of the system performance.

4.4. In Situ Bias Calibration

An in situ bias calibration was done by comparing sensor readings taken when the telescope operator stacked the array at different temperatures or gaps. The stacking procedure puts strong constraints on the relative segment tip and tilt in the array, but no constraint on the relative segment piston. Piston errors that accumulate while the primary is not under SAMS control, due to stacking errors or due to the growing sensor biases are not controllable currently on a real time basis. In order to minimize the unknown piston error, we solved a piston only control equation between the references. The piston only control equation is the pseudo-inverse of the piston only influence function. The piston only influence function is a matrix equation which gives the response of the sensors to a change in the piston of the segments: the tips and tilts are assumed to be well constrained.

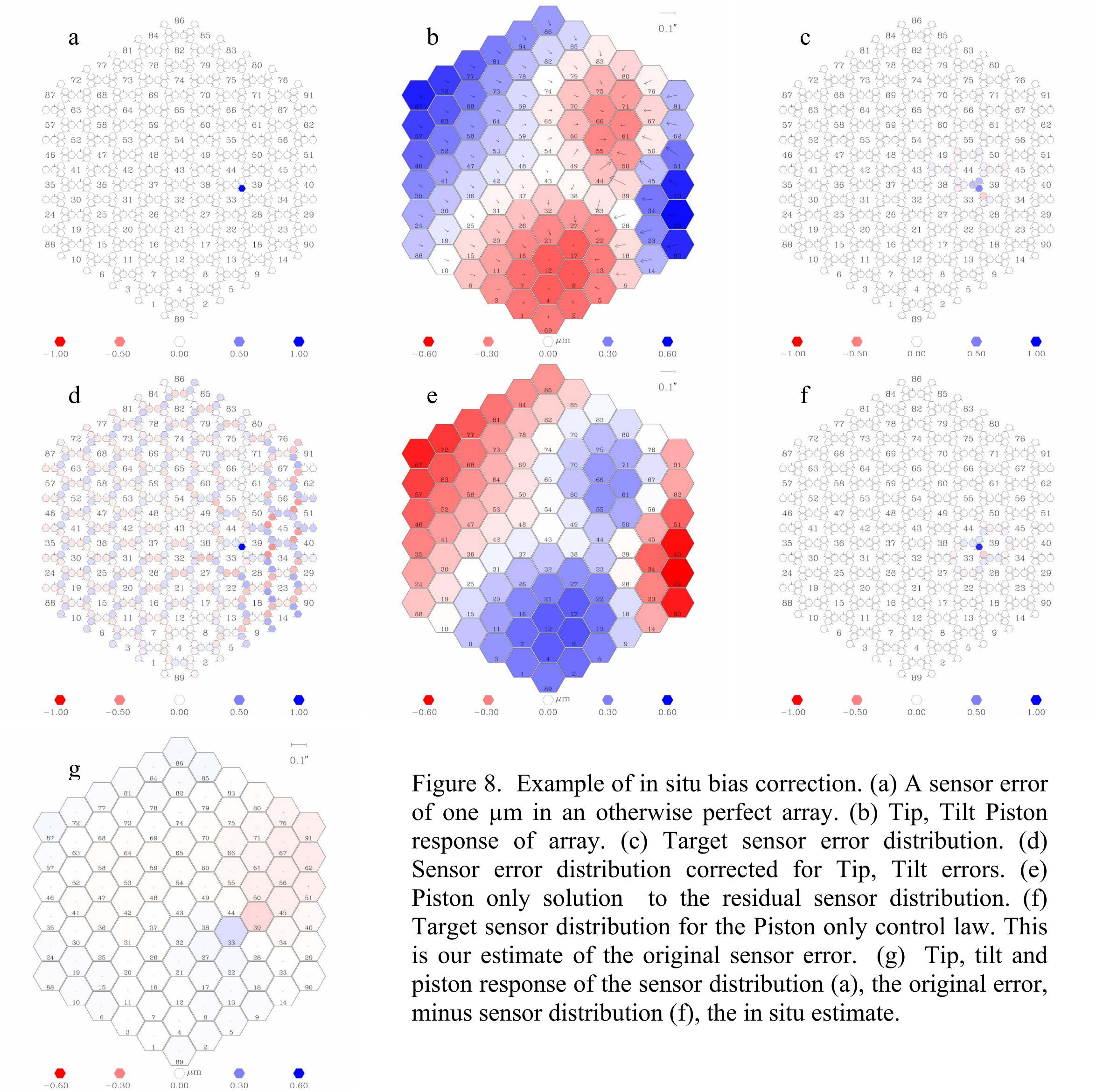

Figure 8. Example of in situ bias correction. (a) A sensor error of one µm in an otherwise perfect array. (b) Tip, Tilt Piston response of array. (c) Target sensor error distribution. (d) Sensor error distribution corrected for Tip, Tilt errors. (e) Piston only solution to the residual sensor distribution. (f) Target sensor distribution for the Piston only control law. This is our estimate of the original sensor error. (g) Tip, tilt and piston response of the sensor distribution (a), the original error, minus sensor distribution (f), the in situ estimate.

The piston only solution minimizes the piston differences between the references, including those due to the sensor biases. The relative piston errors were then subtracted from the sensor shear readings to give an estimate of the sensor bias. These bias estimates were then correlated with gap and temperature to get an estimate of the systematic drift. The biases derived this way have errors which will drive piston offsets in the array, but they do not drive tip/tilt offsets (see fig. 8g). The piston errors introduced this way are however well within the HET error budget of 10µm rms.

5. CURRENT STATUS

We have implemented gap based sensor correction of the SAMS edge sensors. With the current calibration the Target RSE grows at a rate of ~ 20nm/°C, which constitutes a 5 fold improvement over the system performance at the start of operations. SAMS has successfully maintained a stack quality of 0.9″ FWHM or better as measured at the primary center of curvature over a 3.6° temperature range. For the current imaging performance levels of the HET this has led to operations with only one stack per night.

6. FUTURE PLANS

The current performance is still not sufficient to maintain the alignment of the primary mirror array to specifications. Without further improvement in SAMS performance the number of stacks needed will increase as the performance of other HET systems improve.

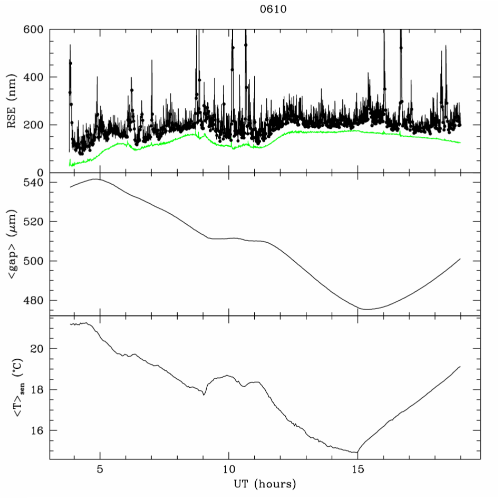

Figure 9. Recent evolution of the Target RSE with gap based sensor bias correction.

The temperature dependent sensor bias of 22+/21 nm/°C measured in the sandwich tests is now a significant factor in SAMS performance. The improved SAMS performance makes possible an improved in situ solution for the bias. We will iterate this calibration technique to improve the solution and to begin separating the temperature and gap effects.

We are constructing a facility to perform direct calibration of the sensors using an automated stage and environmental chamber

7. ACKNOWLEGEMENTS

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