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ABSTRACT

To improve the image quality performance of the Hobby-Eberly Telescope's (HET) segmented primary mirror and to assist in the requirements definition for an optical alignment sensing and control system, multiple engineering tests have been designed and executed. The most significant of these tests have been the alignment maintenance baseline and solid mount tests. Together, these engineering tests defined the complex thermal and non-thermal response modes of the steel HET primary mirror truss and quantified the performance of the segment support system. We discuss the configuration and performance of the HET primary mirror, and discuss our engineering test motivation, goals, design, implementation and results. We also discuss the implications of our primary mirror performance test results for conceptually similar next generation telescope designs, such as the Extremely Large Telescope (ELT).

Keywords: Hobby-Eberly Telescope, mirror alignment, segmented mirror, primary mirror truss

1. INTRODUCTION

The 9.2m Hobby-Eberly Telescope (HET) was designed and constructed on behalf of an international collaboration of five universities: The University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. Astronomers at Texas, Penn State, Stanford, München and Göttingen have access to HET night-time hours in the following percentages, respectively: 52%, 31%, 7%, 5% and 5%.

HET is located at the University of Texas at Austin McDonald Observatory (hereafter simply "McDonald Observatory") in the Davis Mountains of far West Texas. The HET facility sits atop Mount Fowlkes, at an elevation of 2008 meters. Mount Fowlkes is 1.5 kilometers from Mount Locke (2079 meters elevation), the site of the McDonald Observatory's 2.7m Harlan J. Smith Telescope, 2.1 Otto Struve Telescope, and 0.91m and 0.76 telescopes. Mount Fowlkes' meteorological characteristics and 1.5 arcsecond median image quality are well-suited to HET's performance and scientific niches.

HET is an innovative optical and near-infrared astronomical telescope. It incorporates several features that are unique among the current generation of 8 - 10 meter class instruments, such as an an Arecibo-like focal surface tracker. HET's primary mirror is also unique: 91 identical segments. These individual segments are combined into a 9.2m primary mirror array that is an unphased, spheroidal surface. Unlike the Keck telescope which uses 36 regularly spaced but irregular segments, the HET uses 91 irregularly spaced but identical segments. The spacing varies from 6 to 25 mm. HET design details are discussed in several recent S.P.I.E. publications.[1,2,3,4,5] The HET's current status and operational capability are described by this and several more recent papers.[6,7,8,9,10,11,12,13,14]

In this contribution, we discuss performance testing of the primary mirror array during the telescope's Commissioning and Early Operations phases. Commissioning began with the first HET spectrum acquisition, using the Upgraded Fiber Optic Echelle (UFOE) spectrograph, on the night 5/6 September 1997. Commissioning continued through September 1999, when the telescope's facilities, optical, mechanical and electrical systems had progressed through integration, verification and test and were sufficiently robust to support substantial science operations. On 1 October 1999, the Hobby-Eberly Telescope transitioned from Commissioning to Early Science Operations. Since this transition, at least two weeks of each month's night-time operations hours have been dedicated to queue-mode observing of TAC-prioritized science targets. Each month's non-science Early Operations nights have been equally divided between engineering and instrument commissioning. The HET's near-term engineering priorities include minimizing dome seeing, improving on-sky image quality and integration of the Center of Curvature Alignment Sensor (CCAS), a shearing interferometer designed for fine primary mirror alignment. Our near-term science instrumentation goals include commissioning: (a) the Low Resolution Spectrograph multi-object slit unit[9], (b) a 0.9 - 1.7 μm, medium resolution spectrometer (JCAM), and (c) a High Resolution Spectrograph (HRS)[12] . The LRS multi-object unit will be commissioned in Spring 2000; JCAM and HRS will be commissioned in Summer 2000.

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In section 2 of this contribution, we provide a brief overview of the HET segmented primary mirror array characteristics and configuration. In section 3, we describe the algorithms that have been implemented at the HET for aligning the individual 91 segments. In section 4, we discuss key results of our HET primary mirror performance test program, including their implications for the proposed next generation of 15 - 50 m astronomical telescopes. We conclude with a summary our results in section 5.

2. PRIMARY MIRROR CONFIGURATION

The HET employs a spherical, segmented primary mirror supported by a steel truss as an essential element of the telescope's low-cost, Arecibo-style design. The primary mirror array is an unphased, spheroidal surface that requires correction by a 4-element Spherical Aberration Corrector (SAC) at the prime focus. The array incorporates 91 identical, 1-meter diameter, hexagonal segments, arranged in a close-packed 10-meter by 11-meter array. Each of these segments is made of low expansion Zerodur glass ceramic, is 50 cm thick and weighs 130 kg. Each segment has been figured to better than 1/15 wave at 6328 Å. Owing to the 26.18 meter radius, each optical surface has only ~ 6 mm of sag. The gaps between the adjacent segment edges are 6 - 25 mm.

Each of the segments is mounted on a modified Hindle mount that includes three tetrahedrons manufactured from 1/2-inch invar bar. These tetrahedrons are supported by compound levers that provide a 10:1 reduction. The levers are controlled by commercial motor micrometers. Each Hindle mount sits atop the 11 meter diameter primary mirror truss, which is kinematically mounted to the telescope structure at three points. The truss is bolted construction and has a lowest structural frequency of > 10 Hz when fully loaded with 91 segments.

During commissioning, the HET truss was gradually populated with the 91 individual segments and the performance of the primary mirror array was improved to a level capable of supporting science operations.

3. PRIMARY MIRROR ALIGNMENT

Development of robust, fast, high performance, operator-friendly algorithms for primary mirror alignment has been a task of considerable importance and priority. The HET primary mirror array is aligned using a laser projector at the center of curvature (CoC), located atop a 90 foot tower. A diverging beam of laser light is passed through a 250 μm diameter pinhole that is located at the CoC, ~ 26 meters from the primary mirror array vertex. This laser light beam spreads out and overfills the mirror segment array. Each segment reflects a cone of light back to a faceplate surrounding the pinhole at the CoC, forming a bright spot on the faceplate. The individual segment spots display encircled energy 50% and 80% diameters (EE50 and EE80), respectively, of ~ 0.60 arcsec and ~ 1.05 arcsec.

Aligning the individual mirrors into a "stacked" array is a problem with three parts. At the start of the process, there is an amorphous blob of poorly aligned mirrors, each seen as a spot at the CoC faceplate. The first task is to identify the location of each mirror's image with respect to a reference mirror (generally segment 43 at the center of the array). The second problem is to calculate the tips and tilts necessary to stack 90 mirrors onto the reference mirror. The third part of the problem is to accurately move the segments.

A Roper Scientific CCD camera images the individual mirror spots at the CoC and permits unambiguous identification of the mirrors. A concentric ring burst pattern is created. Each ring contains multiple segment images. An automatic pattern recognition algorithm identifies each laser spot based on radius of the ring and angular position within a ring.

If there were no mirror mount or actuator hysteresis, and if there were closed-loop alignment maintenance control of the individual segments, it would be straightforward to command each segment and stack the array. Moving each mirror accurately onto the reference mirror would quickly yield an array stack with a small angular diameter. However, hysteresis exists, likely in both the mirror mount and actuator hardware, and there is, as yet, no closed loop segment control.

Hysteresis effects are partially overcome by, after the burst, moving every mirror spot in the pattern back towards the reference mirror, by twice the distance of the burst move. This generates the "anti-burst" pattern at the CoC faceplate. The position of a given mirror spot is thus roughly the same distance from the reference mirror spot but in the opposite direction. The mid-point of the line connecting the burst and anti-burst segment location on the faceplate is taken to be the starting location of the mirror spot. Segment tip and tilt can be computed which will move the laser return spot from each mirror onto that of the reference mirror.

Rapid progress was made implementing the burst / anti-burst alignment procedure. Still, HET alignment capability was far from specification. At this point, it was realized that although the sequence of motions described above reduced the effects of mechanical hysteresis, it did not eliminate them. There is residual hysteresis in the final move to the reference mirror. Fortunately, this hysteresis is sufficiently stable in time that it can be characterized by monthly empirical assessment. This monthly hysteresis assessment requires 4 - 5 hours of engineering time to characterize all 91 primary mirror segments. Because the tracker blocks some of the mirrors, the hysteresis assessment procedure must be run twice, once for each side of the mirror.

To provide fine tip / tilt alignment and periodic assessment of segment piston, as a follow-on to the coarse alignment burst / anti-burst algorithm, a center of curvature alignment sensor (CCAS) was purchased and delivered to HET early in the construction phase of the project. For tip / tilt alignment, the CCAS uses a dual-arm polarization shearing interferometer. Light from a HeNe laser is projected down to the HET primary mirror, where it is reflected back to a focus at the faceplate of the CCAS, 26.1 meters from the primary mirror array vertex. The reflected, focused HeNe light then passes through a pinhole in the center of the faceplate and enters the interferometer. It is then collimated and split into two separate beams, each of these arms enters a pair of Wollaston prisms, which accomplish the image shearing.

Unfortunately, the CCAS hardware and software were delivered long before any significant number of segments had arrived on-site. Only cursory on-site testing of the device was performed by the contractor. By the time the primary mirror array was populated enough for meaningful engineering testing of the CCAS hardware and software, the contractor had gone out of business and key individuals could no longer be involved, even as independent consultants. Given this history, it is not surprising that the CCAS has proven problematic. As of the end of commissioning, the CCAS still had no role in HET primary mirror alignment other than its use as a laser projector for coarse alignment stacking. Recent extensive engineering testing (August 1999 - February 2000) of the tip / tilt fine alignment arm of the CCAS have proven the physical optics. HET operations and McDonald - Austin engineering personnel are continuing their joint, intensive effort to assess the long-term role of the CCAS at HET. Completion of this effort requires integration, verification and test of the electronics and the 8,000+ lines of software that process the fringe data. We expect this effort to conclude by May 2000.

4. PRIMARY MIRROR PERFORMANCE EVALUATION

Beginning in Fall 1998, a long-term engineering test program was begun to quantify, understand and diagnose the performance and open loop de-stacking of the primary mirror array. These tests were especially critical since the observed de-stacking significantly exceeded that predicted by design analyses. More frequent primary mirror re-alignment was required. The HET design concept was that $\leq 10\%$ of the night-time hours would be used for primary mirror alignment. Early engineering evaluations of the as-built telescope on the sky demonstrated that primary mirror alignment consumed ~ 25% of the night time hours.[7] Under normal operating conditions, the primary mirror must be re-aligned every 20 - 40 minutes, rather than the expected frequency of no more than once per 60 minutes.

To track long-term progress in the primary mirror tip and tilt alignment performance, a simple metric was constructed, as given by equation - 1.

$$F = f(\text{number of segments})\, f(\text{alignment time})\, f(\text{image quality}) = N / t\, I \qquad (1)$$

N is the number of segments being aligned, t is the time (minutes) required for execution of the burst / anti-burst alignment process at the CCAS faceplate, and I is the resultant image quality (EE50, in arcseconds) of the HET stack at the faceplate.

The figure-of-merit, F, increases as: (a) more segments are installed, (b) the time required for primary mirror array alignment decreases, and (c) image quality improves. Mirror installation is complete, hence N = 91. The HET technical specification calls for primary mirror alignment to consume no more than 10% of the night-time operations hours. The original HET operations concept called for re-stacking the primary mirror array once per hour, with coarse and fine alignment procedures that used no more than 6 minutes per hour (i.e., $\leq 10\%$ of each hour). HET requirements specify that the primary mirror array should deliver an image quality of 0.56 arcseconds, within 0.50 arcminute of field center, and in the absence of seeing. This specification applied at the CCAS faceplate, where coarse stacking occurs, though images formed at the CCAS faceplate are obviously affected by dome (but not atmospheric) seeing.

The primary mirror figure of merit would achieve F = 2,465 if the HET were operating at specification (N = 91 segments, t = 6 / 91 ~ 0.066 minutes per segment, I = 0.56 arcseconds). In May 1997, the HET primary mirror figure of merit stood at F ~ 0.3 (N = 7 segments though nearly all were installed, t = 5.0 minutes per segment, I = 4.50 arcseconds). At the end of the commissioning period, 1 October 1999, when science operations commenced, the HET primary mirror had achieved F = 1,286 (N = 91 segments, t = 0.077 minutes per segment, I = 0.92 arcseconds). The net gain in the primary mirror figure of merit, was more than three orders of magnitude: F(1 Oct 99)/ F(1 May 97) ~ 4,133. Of this amount, the increase in the array size yielded a factor of 13.0, improvements in image quality yielded a factor of 4.9, and the decrease in the alignment time per segment improved by a factor of 65.0. At the end of commissioning, HET had a fully populated segment array, and was within ~ 15% of its alignment time per mirror specification. Image quality at the CCAS faceplate was still a factor of ~ 1.5 above the requirement.

Beyond this high-level tracking of the HET primary mirror performance, there is an obvious need to quantify, understand and diagnose the motions of the individual segment supports that cause the array to de-stack on 20 - 40 minute timescales. Figure-1 illustrates the high-level decision tree that the primary mirror performance tests were designed to address. As shown in this figure, the stack degradation has its origins in physical effects that are either thermal or non-thermal.

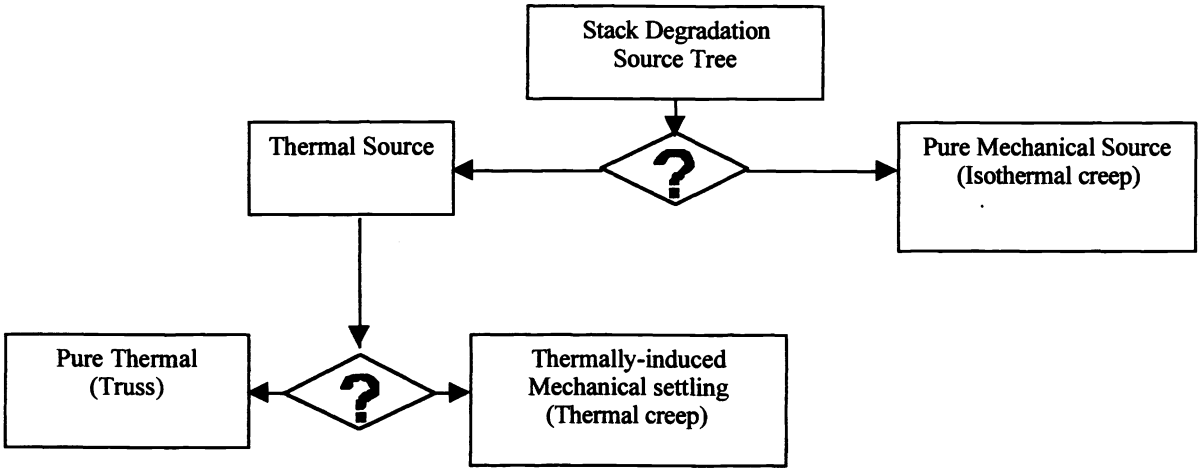

Figure-1: Primary mirror stacking degradation source tree

The possibility existed that a significant fraction of the de-stacking was being caused by mechanical problems (e.g., isothermal creep by the blade flexures in the individual segment mounts), that some component of the whiffletree was failing. However, a series of bench and on-truss tests on the segment mounts established that this was not the case, that there was no large stack degradation source in the mechanical mounts, an important result.

Additionally, there was some concern that rotation of the structure was inordinately shaking the primary mirror array and causing measurable stack degradation. All telescope operations require rotation of the structure from the stacking azimuth, at the CCAS faceplate (azimuth 68 degrees) to the target azimuth. The HET structure rotates on eight 36-inch diameter air bearings. These air bearings provide a controlled lift of ~ 5 mm at pressures of ~ 20 psi permit the structure to be rotated using two rubber-tired friction drives that operate directly against the telescope pier. Engineering tests were conducted to determine whether structure rotation and/or shake caused any portion of the observed mirror de-stacking on-sky. All engineering tests have demonstrated that the structure rotates very smoothly. No primary mirror alignment degradation has ever been detected due to lifting, rotating or setting down the structure onto the pier.

Given these and other test results, our attention was soon focussed on the thermal side of the de-stacking decision tree. The first possibility is that the stack degradation has a purely thermal origin. In this scenario, the stack degradation occurs because the steel primary truss undergoes a large-scale, bulk focus motion as the ambient temperature changes, which changes the radius of curvature in response to a heating or cooling temperature gradient. The individual segments sit atop the truss and are not being compensated -- moved in tip / tilt / piston -- to compensate for any such bulk motion. Hence, the primary mirror array gradually de-stacks as the night-time temperature changes. A zero order calculation of the impact of such bulk motion on the truss and array radius of curvature is straightforward. The change in the truss' radius of curvature is ~ C dT, where C is the thermal expansion coefficient of the primary truss steel, and dT is the temperature change. The HET primary mirror truss steel has a coefficient of thermal expansion (CTE) of 11.5 x 10^{-6} / deg C. Thus, a 1 deg C temperature drop changes the radius of curvature by 300 μm, a amount equal to the radius of curvature tolerance for the optical design of the SAC.

A second possible thermal source for the stack degradation is thermally-induced mechanical settling, "thermal creep". Precise mechanical systems such as the lever arm assembly use to support and align the mirror segments store strain energy at bearing points due to the frictional nature of these connections. Such points are subject to small movements caused by the relative expansion and contraction of components forming the connection, such as a bearing pin in a bronze journal.

For this test, we removed the possibility of such motion by removing the support mechanisms containing frictional bearing points from eight so-called "solid mount" mirror segments. The support mechanisms were replaced by solid Invar rods, joining the whiffletree assemblies directly to the mirror support frame. Teflon balls normally forming the nine contact points between the segments and their supports were replaced with ground steel balls. With these modifications, we effectively created eight test segments that were immune to thermally-induced creep. By comparing the behavior of these mirror segments to their steerable counterparts, we were able to determine whether thermally-induced creep was a factor in relatively rapid mirror de-stacking.

Under subheadings 4.1 and 4.2, we detail the two key tests that quantified the character of the individual segment motions as the primary mirror de-stacks. We discuss the goals of each test, the procedure, and the insights gained into the HET primary mirror array performance . Subheading 4.1 describes the alignment maintenance baseline (AMB) tests; subheading 4.2 describes the complex solid mount tests.

4.1 Alignment Maintenance Baseline (AMB) Tests

As the primary mirror array increased from 41 to 66 segments, substantial testing of the alignment and control algorithms for the primary mirror was enabled. Simple qualitative tests conducted while the array was thinly populated, during Spring 1998, had indicated that the array's image quality was degrading faster than predicted by design analyses. Thus, beginning in late Summer 1998, McDonald West Texas and Austin engineering staff designed and initiated controlled tests to quantify the open loop de-stacking of the primary mirror array. The first set of such experiments were known as the "alignment maintenance baseline" (AMB) tests. More than 20 AMB tests were conducted between 8 September and 6 October 1998.

The AMB test procedure began with a primary mirror stack of all the segments at the CCAS faceplate. During these tests, 66 segments were installed in the truss, After alignment, the primary mirror stack was then observed for ~ 60 minutes, while the telescope remained pointed at the CCAS faceplate. The stack was periodically sampled by the CCAS imager and the stack image quality (EE50, EE80) was evaluated and recorded.

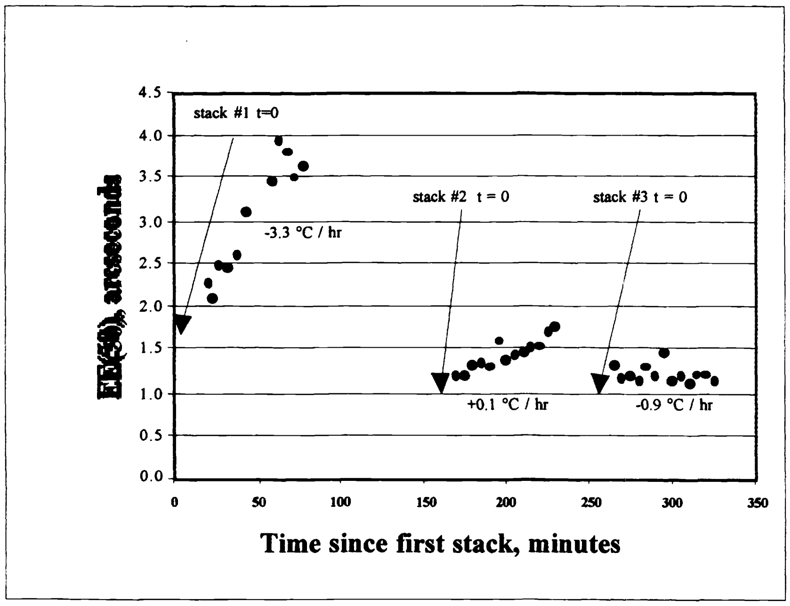

Figure-2: Three Alignment Maintenance Baseline Tests: 2/3 October 1998

Figures-2 illustrates typical primary mirror array performance during the AMB test phase. It plots the results of three successive AMB tests that were conducted by the engineering staff at HET on the night of 2/3 October 1998. Time t = 0 corresponds when the first primary mirror alignment stack was completed at the CCAS faceplate (23:20 CST). Three sequences of primary mirror EE50 are seen in Figure-3, each of which represents an AMB test. Alongside each AMB test's points is the ambient temperature gradient observed during that test. Thus, during the first, second and third AMB tests, the ambient temperature gradients were -3.3, +0.1 and -0.9 deg C / hr, respectively.

Several points are worth noting with regard to Figure-2. As on most nights, the ambient temperature gradients on the night of 2/3 October 1998 were larger in the evening than in the morning. Since open loop control of the HET primary mirror assumed that the ambient temperature gradient would be ≤ 0.5 deg C / hour, the primary mirror will certainly de-stack when the temperature gradient is -3.3 deg C / hour, as it was during the first AMB test on 2/3 October 1998. Under clear to partly cloudy sky conditions, meteorological conditions in West Texas typically yield stable temperature gradients only in the early morning hours, with the 2 - 3 hours prior to morning astronomical twilight being the most benign.

Large evening primary temperature gradients make the initial stack difficult to achieve. This is readily seen in Figure-2, where the first stack achieved EE50 ~ 1.6 arcsec, while stacks 2 and 3 achieved EE50 ~ 1.1 arcsec. Evening primary mirror stack quality, as measured by EE50 and EE80 immediately after completion of the stack, is almost always worse than morning primary mirror stack quality. Note also that the rate at which the primary mirror array unstacks is higher in the evening than in the morning, as in Figure-3, where the de-stacking rate for stacks 1, 2 and 3, respectively, was 0.030, 0.0084 and -0.0011 arcseconds per minute.

The ambient temperature gradient for each of the 2/3 October 98 AMB tests is shown in Figure-2 alongside each test's data. Note that the de-stacking is not strictly correlated with the temperature gradient during a given test. For example, stack-2 degraded faster than stack-3, even though the stack-3 temperature gradient (+0.1 deg C / hr) was nominally more benign than the stack-2 temperature gradient (-0.9 deg C / hr). This is, at least in part, an observable consequence of the thermal lag times for the HET primary mirror truss components. The truss consists of relatively long, thin, low mass struts and roughly spheroidal, thick, massive nodes that connect the struts. The truss struts are have relatively fast thermal response times, compared to the substantially more massive, thermally slow truss nodes. Note that, during construction, the thickness and surface aspect ratios of all the truss members were selected to ensure comparable thermal performance and avoid bi-metallic bending.

Table-1 summarizes all AMB test results. The columns labeled "start" and "end" are the statistics for the measured CCAS image quality at the beginning and end of the AMB tests. The column labeled "degradation" is the observed de-stacking of the primary mirror, as measured at the CCAS faceplate, in arcseconds per hour. Note the substantial difference between the median and the mean. This difference is caused by the tail of the distribution which has several particularly large temperature gradients, almost always observed at the beginning of the night. Note that, at the time these data were acquired, typical HET stack image quality was EE50 / EE80 ~ 1.2 / 2.0 arcsec. These have been improved to their current (February 2000) performance level of EE50 / EE80 ~ 0.9 / 1.6 arcsec.

Table-1: September / October 1998 Alignment Maintenance Baseline Results Summary

	START (arcsec)		DEGRAD (arcsec/hr)		END (arcsec)	
	EE(50%)	EE(80%)	EE(50%)	EE(80%)	EE(50%)	EE(80%)
Average	1.22	2.08	0.62	1.31	1.82	3.39
Median	1.20	2.02	0.32	0.46	1.52	2.48

4.2 Solid Mount Tests

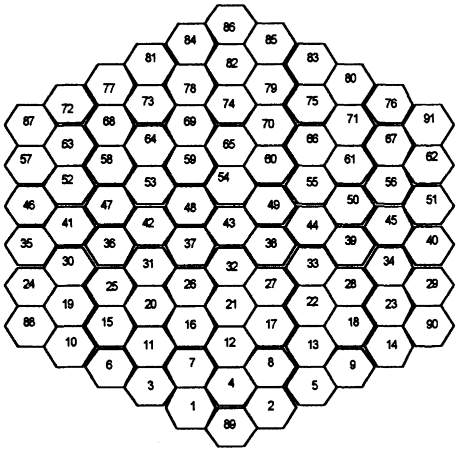

Figure 3: Primary Mirror Array

Since the AMB tests tracked the effects of the individual segment motions on the primary mirror stack, the logical follow-on to the AMB tests was a more complex engineering test sequence designed to measure and diagnose the individual segment tip / tilt de-stacking motions. Such tests were designed by McDonald Observatory Mechanical Engineer John Booth, in collaboration with the HET West Texas operations staff. These took the form of a set of "solid mount tests". The solid mount tests measured the individual segment motions relative to the large-scale, thermally-induced deformation of the truss that effectively deforms the primary mirror array on timescales of a few tens of minutes.

The solid mount test plan began with the design of modified mount hardware for 8 of the 91 HET mirror supports. Each of these eight modified mounts became "solid mounts". For each of these mounts, we built a solid connection between the support whiffletree and the truss by replacing the actuator / lever assemblies with small Invar™ posts. The purpose of this substitution was to provide a solid, thermally invariant connection between the mirror support whiffletree and the primary mirror truss for each solid mount mirror. Because they were attached to the primary mirror truss in this manner, the solid mount mirrors mimicked truss motion and would show no de-stacking owing to any mechanical problems with the supports, even if such problems existed.

Eight mirror supports were selected for modification as a compromise between our need for a statistical sample and the significant labor and time required to de-install, modify and re-install mirrors and their supports. Since, in broad brush, segment de-stacking tip and tilt motions had been observed to increase with increasing distance from the primary mirror vertex (near segment 43), the segments chosen to be the solid mount mirrors were in ring-4 of the array (Ring numbers are measured from the center outward. The outermost is ring-5.). The supports for ring-4 segment numbers 4, 15, 18, 41, 45, 68, 71 and 82 were selected for the solid mount modifications. Figures-3 and -4 illustrate the locations of these segments on the primary mirror truss. Segments in ring-5 were not selected because we wanted to observe their large unconstrained tip / tilt motions with respect to well-controlled neighbors. Outside of the solid mount mirror tests, the solid mount segments were covered.

Figure-4: HET primary mirror array, with solid mount segments covered.

After installing each of the modified, solid mount mirrors into the truss, they had to be accurately re-pointed so that their laser returns could be observed at the CCAS faceplate in a sensible pattern. They also had to be focussed. With unmodified mounts, pointing and focussing a re-installed segment is straightforward. However, since they lacked key motion hardware components, the solid mount mirrors had to be manually re-pointed using the large 1/4-20 and M30 coarse adjustment screws. Re-pointing and focussing the solid mount mirrors required three successive half-nights of engineering time.

During each test, solid mount mirror motions were compared to adjacent, unmodified mirrors and mirror supports. Accurately measuring the complex de-stacking tip / tilt motions of nearby sibling mirrors with respect to the solid mount mirrors was the primary test objective. The tip / tilt motions of the individual solid mount and non-solid mount mirrors (hereafter "sibling mirrors") were measured with respect to a reference frame defined by the aggregate of the solid mount mirrors. This reference frame was adopted because these tests were conducted by observing each mirror's laser return at the center of curvature faceplate, which sits atop a 90 foot tower. This tower consists of an inner 4 foot diameter cylinder and an outer 6 foot diameter tower. All center of curvature instrumentation, including the faceplate, is mounted to the inner tower, which has provision for vibrational isolation from the outer tower. However, since the solid mount tests must observe segment tips and tilts to an accuracy of ~ 0.05 arcsec to accomplish the test objectives, residual tower sway of ~ 100 - 200 μm can be a significant error source. addition to concerns about tower sway in the wind, the best-focus position of the CCAS faceplate varies with temperature. These issues were eliminated by the above choice of reference frame.

Nine solid mount tests were executed as part of HET engineering operations in October and November 1998. An entire night was generally required for each test. After two trials, the remaining tests each ran for more than five hours. Each of these tests used all eight solid mount mirrors. To maximize the observability of segment tip / tilt motions, the solid mount tests were begun as early in the evening as possible. This guaranteed relatively large temperature gradients.

Each test began by manually positioning the eight solid mount mirrors approximately at the vertices of an octagonal pattern on the faceplate. The angular distance between adjacent solid mount segment laser returns, at the faceplate, was set to ~ 10 arcsec at the beginning of each test. To avoid confusion, all segments that were not participating in a given test were driven significant distances in tip and tilt so that their laser returns could not possibly be observed at the faceplate during the test.

Once the solid mount laser returns were positioned at the faceplate, the selected sibling segments were moved to the vicinity of the solid mount return. For ease of tracking during the test and data analysis, each sibling segment's laser return spot was positioned near the solid mount segment whose truss position was similar. Thus, segment 12 was often the sibling for solid mount segment 4. Its laser spot was positioned near that of segment 4 on the CCAS faceplate, at the start of each test. Care was taken to position the sibling segment image near the solid mount segment image, ~ 5 arcsec, but not so close that the segment and sibling images would merge during the test and no longer be distinguishable.

Prior to the test start, the sibling mirrors were focussed. Since focus motion moves the laser returns at the CCAS faceplate, focus mimics de-stacking. Thus, the Telescope Operator was instructed not to re-focus the sibling mirrors during the tests unless the spot return image quality degraded such that it compromised the test's goals. The sibling mirrors were never re-focused more than once in any solid mount test. Focus was removed from the recorded segment tip / tilt motions in post-test modeling.

Throughout each solid mount test, the tip and tilt motions of all sibling and solid mount segments were measured with respect to the aggregate solid mount segment reference frame. Data were acquired every five minutes. The test duration ranged from 95 - 315 minutes.

Figures-5, -6 and -7 illustrate several types of segment behavior observed in the solid mount tests. The filled points correspond to the data from the solid mount segments; the unfilled points are data for the sibling segments.

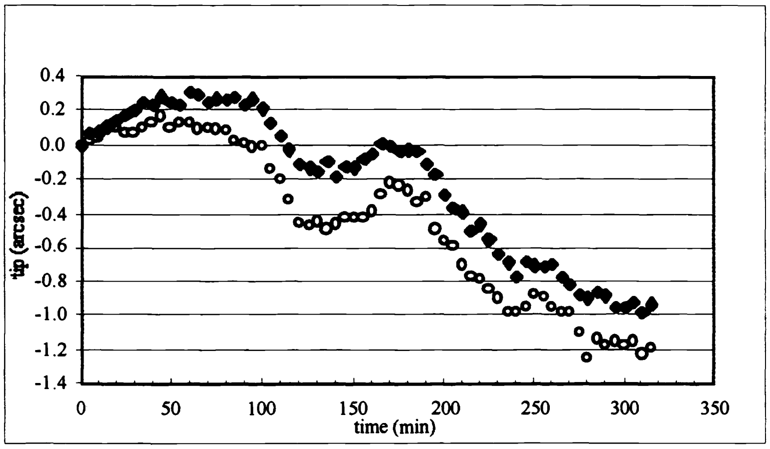

Figure 5: Tip versus time for solid mount segment 4 and sibling 12, test #4

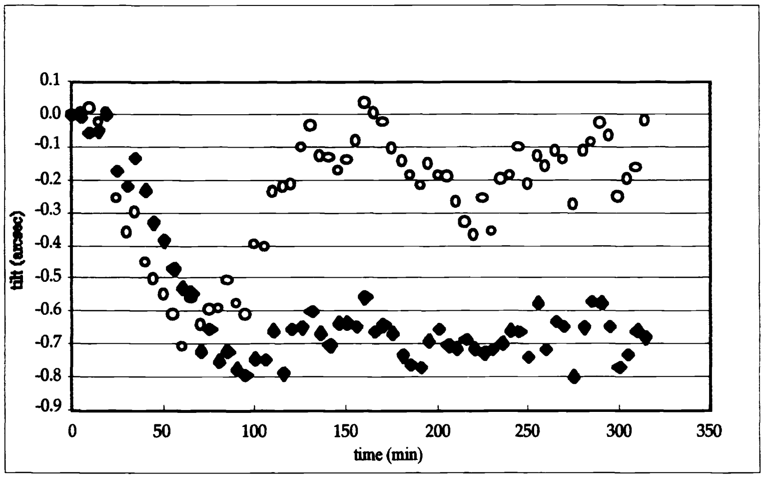

Figure 6: Tilt versus time for solid mount segment 45 and sibling 50 in test #5

Figure-5 plots tip versus time for solid mount segment 4 and sibling segment 12 during test #4. These segments are located at the base of the truss. During this 315 minute test, the mean primary mirror truss temperature varied from 16.6 deg C at the test start to 14.4 deg C at test end, yielding a mean temperature gradient of 0.42 deg C / hr. The temperature variation was not linear however, and the gradient exceeded the HET specification for at least 40% of the test duration. Throughout all of the solid mount tests, the mean primary mirror truss temperature was computed from the ensemble average of 50 temperature sensors located on the truss. Note, in Figure-5, the similarity in behavior shown by the solid mount and sibling segments. Though their individual behavior is non-linear, they track each other well. Note also the complexity and magnitude of the motions of these segments. The peak-to-peak tip range is ~ 1.0 - 1.2 arcsec, a considerable motion..

These segments are located at center right on the truss, as viewed from the center of curvature. During this 315 minute test, the mean primary mirror truss temperature varied from 9.5 deg C at the test start to 8.2 deg C at test end, yielding a mean temperature gradient of 0.25 deg C / hr, nominally within the HET specification. Again, however, within the test, the temperature variation was quite non-linear. Most the temperature drop occurred in the first 90 minutes (9.5 to 8.5 deg C). The temperature then continued to trend downward, with oscillations of ~ 0.1 - 0.15 deg C on timescales of < 1 hour. In this case, the solid mount and sibling segments

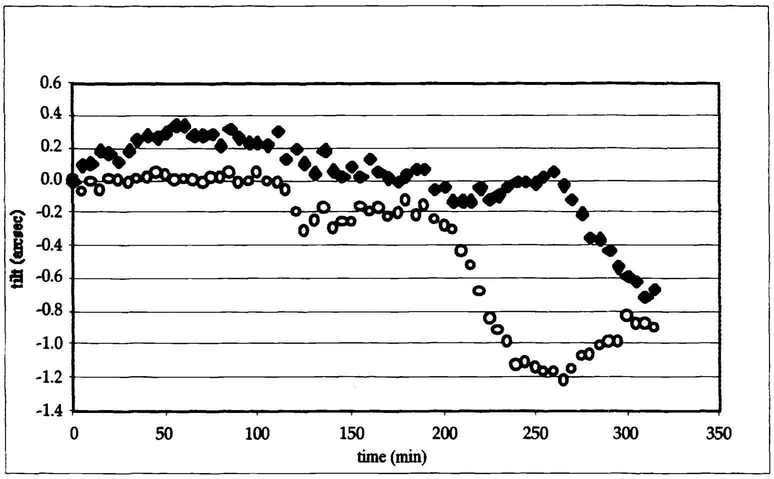

Figure 7: Tilt versus time for solid mount segment 45 and sibling 50 in test #4

show qualitatively similar behavior only for the first 90 minutes, after which their behavior markedly diverges. The solid mount segment moved very little for the remainder of the test, while the sibling showed substantial motion, ~ 0.7 arcsec, that does not track the solid mount segment motion.

Figure-7 also plots tilt versus time for solid mount segment 45 and sibling segment 50, but during test #4. Compare their behavior here to that shown in Figure-9 (test #5). In this case, the solid mount and sibling segments show qualitatively similar behavior for the first 200 minutes. The sibling segment then moved substantially in negative tilt. The solid mount segment followed it, but not for another hour. These differences have the characteristics of small scale, thermal lags in the primary mirror truss.

The solid mount tests provided numerous examples of the types of motions shown in Figures-5, -6 and -7. Throughout these tests, the solid mount and adjacent mirrors behaved similarly in the mean. But substantial structure was observed in many tests on scales ~ 0.1 - 1.0 arcsec in relative tip and tilt motion. These data demonstrate the complexity of the underlying primary mirror truss motions. Though there is undoubtedly a bulk truss motion component, and it is sometimes observed well (e.g., in solid mount test #1), the small scale complexities and higher order motions of the primary mirror truss usually obscure the large scale response of the truss to thermal gradients.

Tests 1, 2, 4 and 5 used the same sibling segments and can be combined. For each solid mount / sibling pair (8 in each test, 32 in the combined four test set), the tip and tilt differences were computed between the start and end of each test. The individual test data were normalized by dividing the tip / tilt motions by the temperature gradient. Thus, in each of the four tests, each observed sibling / solid mount pair yielded a quantity that characterized the range of relative solid mount / sibling motion per unit temperature change. The distribution of these quantities, across all four tests, was zero mean and approximately Gaussian. The mean (sibling - solid mount) tip difference between the start and end of tests 1, 2, 4 and 5 was $\mu \sim -0.06$ arcsec/deg C, with a standard deviation per observation of $\sigma \sim 0.50$ arcsec/deg C; the mean (sibling - solid mount) difference in tilt, between the start and end of all tests was $\mu \sim 0.16$ arcsec/deg C, with a standard deviation per observation of $\sigma \sim 0.38$ arcsec/ deg C.

The fundamental conclusion of the solid mount tests is that the individual tip / tilt motions of the HET segments (which are unconstrained, operating open-loop) are too large and complex to maintain acceptable on-sky image quality for more than 20 - 40 minutes without some form of closed loop control. The individual segment support structures do not appear to be a principal source of the primary mirror array un-stacking. The major de-stacking driver is primary mirror truss motion, underneath the segments and the segment supports. One likely cause of the observed complex truss motion is the contrast between the thermally massive, slow primary mirror truss nodes and the thermally light, faster truss struts. Some predictive capability for these modes has been demonstrated via Finite Element Models that incorporate rigorous physical representations of the truss characteristics and thermal physics. But the predictive capability of even fairly complex models has fallen short of that required to maintain the image quality demanded of a 9.2m telescope doing astronomical research with spectrometric CCD exposures of 30 minutes to 2 hours duration. Note that a primary mirror truss made of Invar, rather than steel, would have slowed the observed individual segment motions by approximately a factor of 5, the ratio of the thermal expansion coefficients of steel and Invar. This would have improved HET open loop performance, but would not have eliminated the need for closed loop segment control at HET.

The solid mount test results provided the motivation for the HET Board of Directors to approve and fund the procurement of a Segment Alignment Maintenance System (SAMS). After extensive in-house discussions and specification development, this contract was awarded to the team of NASA Marshall Space Flight Center (Huntsville, Alabama, USA) and Blue Line Engineering (Colorado Springs, Colorado, USA) in September 1999. The NASA / Blue Line team SAMS system concept employs inductive edge sensor technology developed by Blue Line Engineering under NASA-sponsored research and development grants. This work also embodies an underlying control strategy based on the pioneering work of Nelson and

Mast. The specifications for this system are such that the HET segmented primary mirror array will require alignment only once every two weeks, reducing alignment night-time overhead to essentially zero. This system is expected to be routinely operational for HET science by late Spring 2001. The NASA / Blue Line Engineering SAMS concept is described in detail in another paper in this conference [14].

These results have clear implications for the design of the next generation telescopes, instruments that will likely be designed with apertures of 15 - 50 m. Since, barring unforeseen optical technological developments, such instruments will be segmented mirror telescopes, it would be unwise to not include the incremental cost (~ 7 - 10%) for a high quality, closed loop control system.

It is virtually certain that any astronomical telescope with an aperture significantly larger than 8 meters will utilize segmented mirrors. Indeed, current concepts for Extremely Large Telescopes[16] employ dozens to thousands of segments that will have to be supported on a rigid space-frame. Our experience shows that even a well engineered structure will have some inelastic properties. This may well necessitate consideration of active structures to maintain segment spacing. A precise segment position sensing system will also likely be part of the system design. The changes due to gravity and thermal gradients will have larger amplitudes than one could correct for using a deformable mirror in an adaptive optics system.

5. SUMMARY

The HET consortium has produced a viable 9.2m segmented primary mirror array on a budget just 15 - 20% of comparably sized telescopes. As of 1 October 1999, this telescope entered its Early Operations phase and began to routinely produce science two weeks each month while continuing with key engineering and instrument commissioning efforts, each requiring approximately one week per month.

This paper has described key portions of the on-going HET primary mirror performance evaluation effort. As of February 2000, the burst / anti-burst alignment algorithm yields primary mirror stacks at the center of curvature with EE50 / EE80 ~ 0.92 / 1.6 arcsec. The incorporation of empirically determined hysteresis corrections into the algorithm markedly improved its performance. During the Commissioning and first four months of Early Operations, the primary mirror performance figure of merit improved by more than three orders of magnitude as more of the array was utilized in stacking, motion controls and communications issued were addressed, and fundamental image quality improvements were made at the telescope.

Substantial efforts have been made to quantify, understand and diagnose the causes of the primary mirror array de-stacking. After completion and analysis of the AMB and solid mount engineering tests, the engineering staff recommended that the Board of Directors fund a Segment Alignment Maintenance System (SAMS). The Board approved such a procurement in Spring 1999, and the SAMS effort is now underway as a joint program between NASA - MSFC and Blue Line Engineering. By Spring 2001, the Hobby-Eberly Telescope will be operating with a closed-loop control system to maintain primary mirror alignment. SAMS will improve the telescope's scientific productivity by at least 25%.

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