Development and performance of Hobby-Eberly Telescope 11-m segmented mirror

Krabbendam, Victor, Sebring, Thomas, Ray, Frank,
Fowler, James

Victor L. Krabbendam, Thomas A. Sebring, Frank B. Ray, James R. Fowler, "Development and performance of Hobby-Eberly Telescope 11-m segmented mirror," Proc. SPIE 3352, Advanced Technology Optical/IR Telescopes VI, (25 August 1998); doi: 10.1117/12.319265

Event: Astronomical Telescopes and Instrumentation, 1998, Kona, HI, United States

Development and Performance of Hobby Eberly Telescope 11 meter Segmented Mirror

Victor L. Krabbendam, HET Project, McDonald Observatory, University of Texas at Austin
RLM 15.308, Austin, TX 78712-1083

Thomas A. Sebring, SOAR Telescope Project, National Optical Astronomy Observatories,
P.O. Box 26732, Tucson, AZ 86726-6732

Frank B. Ray, McDonald Observatory, University of Texas at Austin,
RLM 15.308, Austin, TX 78712-1083

James R. Fowler, HET Project, McDonald Observatory, University of Texas
PO Box 1337, Fort Davis, TX, 79734

ABSTRACT

The Hobby Eberly Telescope features a unique eleven-meter spherical primary mirror consisting of a single steel truss populated with 91 Zerodur™ mirror segments. The 1 meter hexagonal segments are fabricated to 0.033 micron RMS spherical surfaces with matched radii to 0.5 mm. Silver coatings are applied to meet reflectance criteria for wavelengths from 0.35 to 2.5 micron. To support the primary spectroscopic uses of the telescope the mirror must provide a 0.52 arc sec FWHM point spread function. Mirror segments are co-aligned to within 0.0625 arc sec and held to 25 microns of piston envelope using a segment positioning system that consist of 273 actuators (3 per mirror), a distributed population of controllers, and custom developed software. A common path polarization shearing interferometer was developed to provide alignment sensing of the entire array from the primary mirror's center of curvature. Performance of the array is being tested with an emphasis on alignment stability. Distributed temperature measurements throughout the truss are correlated to pointing variances of the individual mirror segments over extended periods of time. Results are very encouraging and indicate that this mirror system approach will prove to be a cost-effective solution for large optical collecting apertures.

Keywords: Spherical Segmented Mirror, Alignment, Large optical telescopes, HET, Spherical mirror telescopes

1. TELESCOPE

The Hobby Eberly Telescope (HET), is an astronomical telescope intended mostly for spectroscopy(1). The telescope configuration is similar to the Arecibo radio telescope, in that it has a fixed primary mirror pointing vector during tracking. The telescope structure supports the primary mirror at a constant 55° elevation and provides full 360° azimuth rotation for coarse positioning. Fine positioning and object tracking is enabled by a star tracker(2) located at the top of the telescope structure. This tracker system moves the telescope's Gregorian corrector and instrument package along the focal surface of the stationary spherical primary mirror to track the apparent motion of celestial objects.

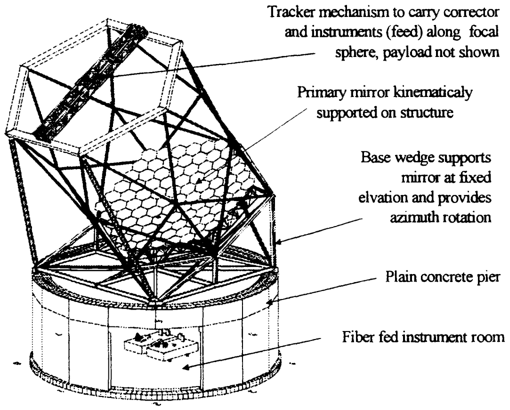

Figure 1: HET Telescope Configuration

The configuration of the telescope, shown in Figure 1, allows access to 70% of the sky normally available in a one year period. The tracker can sweep a 12° square field of view allowing observation times to range from 0.75 to 2.5 hours depending on azimuth and target position. Figure 2 shows the corrector pupil on the primary array and depicts the nature of the roving aperture across a stationary primary.

Part of the SPIE Conference on Advanced Technology Optical/IR Telescopes VI • Kona, Hawaii • March 1998
SPIE Vol. 3352 • 0277-786X/98/$10.00

Two descrete periods of an observation are shown. The left image is the beginning of an observation in the west and the right image is during the middle of an observation where the object is momentarily telecentric.

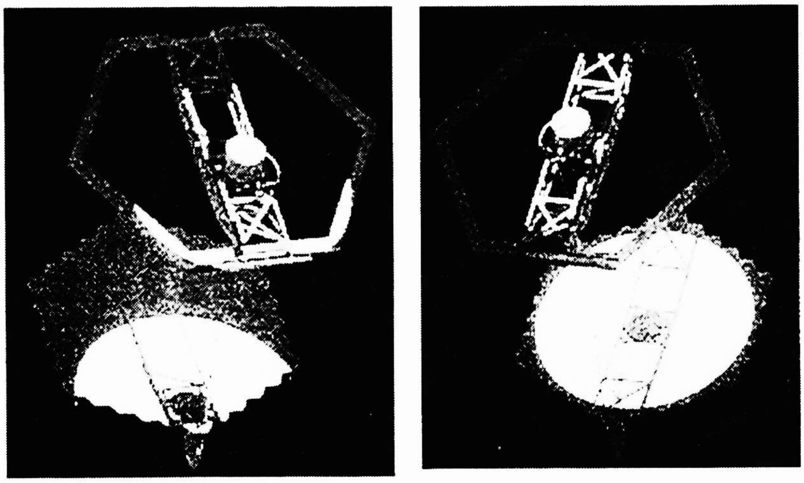

Figure 2: Illustration of moving pupil on primary mirror

Sebring et. al.(3) describe the many configuration issues evaluated to determine the specific configuration of the telescope. Many of the built in physical limits are included because other science or instrument limitations also exist. Due to the cost constraints of the project the HET development exploits every opportunity to simplify the design and construction of the system. The HET does requires innovative operation approaches and unique observation planning(4) but any limitations are offset by significant construction cost advantages.

The overall performance of the telescope within its local enclosure is targeted for 0.65 arc seconds full width half maximum encircled energy. This performance insures a seeing limited operation for the site at the McDonald Observatory in West Texas. The telescope is expected to operate primarily in a queue-scheduled mode. Between observations, for a maximum time allotment of 10% , the telescope's hardware systems (mainly the mirror) are given system access to update and recalibrate.

2. MIRROR CONCEPT

2.1 Mirror Hardware and Configuration: The HET primary mirror is an array of 91 segments which form a spherical collecting aperture 11 meters point to point, 10 meters flat to flat, and 77.6 square meters in collecting area. The mirror substrates are 50 mm thick Zerodur™, polished and then coated with an enhanced silver coating. Each mirror segment is supported by an individual, modified Hindle, support system which has an integral set of actuators to control segment position. The segment supports provide the connection to the single steel truss that supports the mirror modules at their positions within the array. The truss is kinematically mounted to the telescope structure, isolating it from structure induced deformation. To sense mirror segment positions, an interferometer resides at the center of curvature of the array. This measures individual mirror pointing vectors as well as mirror phase or piston errors. A distributed temperature measuring system throughout the mirror truss is provided as input to thermal compensation algorithms. A linked computer system receives thermal data, evaluates conditions, processes segment position actuator commands, and conducts resource allocation for control of the array.

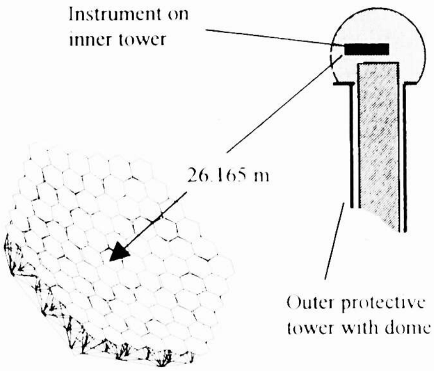

Figure 3. Main mirror array and interferometer atop center of curvature tower.

2.2 Operating Concept: The baseline mirror control concept is to update alignment of the mirrors from instrumentation at the center of curvature between scientific observations. In between alignments the temperature sensors will measure thermal changes and feed algorithms that predict the thermo-elastic behavior of the truss and hence the pointing of the segments. This predictive system will operate at low bandwidth, but constantly during observations to reduce the rate of alignment decay and prolong the span between periodic optimization via interferometric measurements. Thermal uniformity throughout the array as well as optimum dome seeing is provided via a high capacity computer controlled downdraft ventilation system, capable of 20 air changes per hour within the dome of the HET. During the day the temperature of the dome interior is to be maintained close to night time temperatures via air conditioning to minimize mirror alignment errors driven by thermal expansion, contraction, and hysterisis of the mirror/support system.

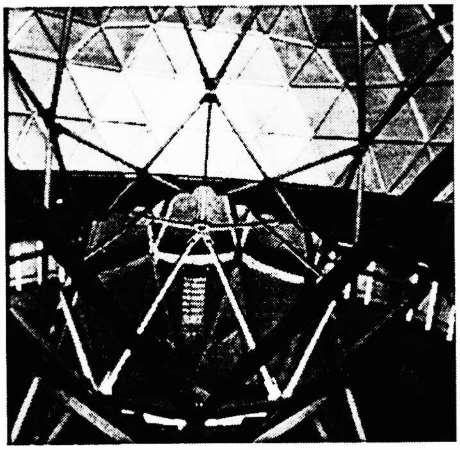

Figure 4. HET showing primary mirror completely populated with segments.

2.3 Engineering Advantages: The primary mirror design concept capitalizes on several key features associated with the HET's overall design. The constant gravity vector provides many advantages with the mirror thickness and support complexity. It eliminates the need to actively compensate for structural deformation of the mirror truss due to changing gravity vectors, and similarly the need for closed loop, high bandwidth mirror alignment sensing and control. Individual segment supports need not accommodate changing gravity loads and hence can be much simpler.

The spherical figure of the primary implies that all mirror segments feature identical spherical optical surfaces, much simpler to fabricate and test than on or off axis aspheres. In addition, the mirror segments are also defined to be identical in size, resulting in additional optical fabrication savings and replicated, identical segment support structures. Regular hexagons do not uniformly tile a sphere, so segment interstitial gaps vary from 6.2 mm to 15.8 mm (5) resulting in less than 1% throughput penalty compared to a constant gap arrays set to the minimum 6.2 mm value.

Due to the untested nature of this mirror system and the associated tracker, the motion of the pupil upon the primary mirror during tracking, and the expense of stellar based focal plane segment position sensing systems, an instrument placed at the center of curvature was chosen for primary mirror calibration. A common path phase shifting, polarization lateral shearing psuedo white-light interferometer was developed for use at the center of curvature with very fine resolving accuracies for both pointing and piston positions. Access to the center of curvature position has provided additional advantages in alignment, characterization tests, and development activities for the mirror without coupling to the complex tracker development exercises or deconvolution of errors induced elsewhere within the telescope system.

3. PRIMARY MIRROR REQUIREMENTS

The HET primary mirror system is specified to provide 0.59 arc seconds FWHM encircled energy. Allocation of all allowable errors is made in the telescope optical performance error budget (6) and the following six key requirements have significant impact on the hardware and development approach to the primary mirror.(7)

- The global array radius must be within +/- 5 mm from the nominal 26,165 millimeter nominal dimension. This implies a rather loose tolerance on actual radius of curvature for the set of segments.
- Each segment's optical figure shall be within $\lambda/15$ RMS of the specified spherical surface and radii must be matched to within 0.5 mm...an extremely tight tolerance on segment-to-segment radius of curvature variation.
- Each segment must be pointed to the same global center of curvature to within 0.065 arc seconds.
- The optical surfaces of the segments must fall within a 0.025 millimeters of the best fit surface for the entire array.
- Re-alignment can take no more than 6 minutes of every hour.
- Lastly the overall quality shall be maintained for 1 hour during a maximum temperature transition of 0.5 °C per hour. Higher temperature changes or longer periods of time have allowable degradations on the order of 10% over 2.5 hours.

4. COMPONENT DEVELOPMENT

4.1 Truss: The primary mirror truss serves as the support structure for the primary array as well as the interface to the telescope structure. It supports the 27,000 pound weight of the mirror modules. Kinematic mounting of the truss provides isolation from varying support conditions from the telescope structure. Sources of disturbance include differential thermal expansion between the truss and the telescope and telescope "racking" from its four leg base being set down at different azimuth positions. Any variation in the support of the truss by the telescope structure can cause only rigid body changes in pointing vector, not primary mirror deformation.

In 1994 Stephen Medwadowski completed a preliminary design of the current truss establishing the 3-node layer form and the baseline member sizes necessary to meet desired structural performance. (8) Subsequent design work devoted significant efforts to details to simplify the manufacturing of the truss by reducing the number of different struts and nodes used. The top layer nodes were repositioned to be in the same relative positions with respect to the mirror modules which each group of three top nodes supports. The mid-layer node level was curved concentric with the front and the geometry was arranged so 91 identical tetrahedron assemblies were formed under each mirror location. These 6-strut, 4-node subassemblies account for every top and mid level node greatly enhancing manufacturability and increasing the dimensional control. In addition, an automated design technique developed to support this optimization exercise provides symmetry of 3 identical sections at 120° with each section also having 2-fold symmetry. (9)

The truss was purchased from Mero Structures, Germantown WI, (Wurzburg, Germany) for $436,000. The fabrication technique was Mero's standard K-strut bolted connections preloaded for equivalence to welded joints. Viability of the bolted joints was demonstrated both via analysis and test of sample nodes. Mero's manufacturing technique of CNC machined forged nodes and automated laser welded struts made production of the truss rapid and efficient. The overall accuracy of the truss is established by the precision of the constituent parts. The accuracies were demonstrated to provide the HET truss center node positions to be within 2 mm of design during a trial assembly of the truss. Shipped in pieces and assembled on site, the completed truss was dimensionally accurate to within the specified 6 mm node position tolerance. A reduction in accuracy relative to the test assembly was a result of field conditions and dimensional changes of components caused by subsequent powder coating. Before the coating the components were hot dip galvanized to assure long life and minimum required maintenance in the operations environment.

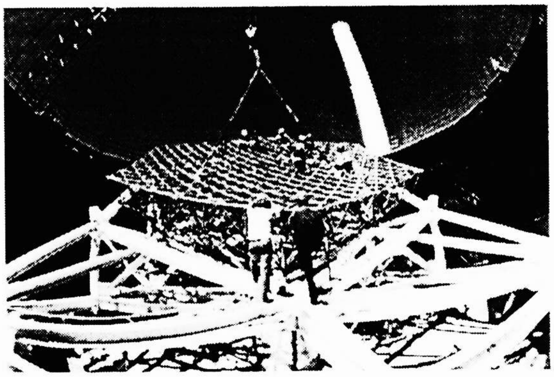

Figure 5. HET mirror shown installed in lower portion of structure

The design of the kinematic mount was a significant technical challenge. Three custom assemblies were developed to isolate the truss from deforming forces. The overall layout is described in Figure 6. Mount I in the lower left (telecentric view) is constrained in X, Y, and Z but allows rotation about X, Y, and Z axis. Mount II is constrained in Y and Z but allows motion in X via a linear roller slide. Locally it is unconstrained in all three rotation axis. Mount III at the top of the truss is only constrained in Z. All other axis are free to move relative to the telescope mounting point. Many bearing assemblies are employed to make up the three mounts including long radius point contact bearings, spherical bearings, linear roller bearings, and ball bearings. The result is an assembly which does not develop a lateral load larger that 25 pounds, (force at M II to overcome stiction in linear slide) and no torque larger than 5 foot pounds if the relative telescope mount locations stay within Z=2 mm or the equivalent angular orientation.

Parameter	Value
Number of Struts	1747
Types of Tubes	5
Number of Nodes	389
Types of Nodes	6
Truss Weight	24,805 lbs
First Mode (freq., fully loaded)	12 hz

Table 1. Truss design and performance values

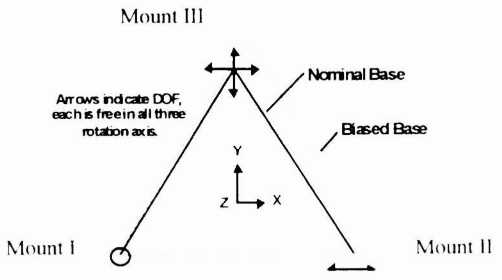

Figure 6. Truss Kinematic Support Configuration

4.2 Substrates: Early development work for this telescope considered the use of 1 meter round borosilicate glass segments. During the last major overhaul of the design in 1994 the segment concept changed to hexagonal shapes for better throughput and IR performance. It was also resolved to make the mirrors of low thermal expansion material to minimize thermally driven radius and figure change of segments. With the shape and material decided the mirror substrate design development focused on the size and thickness for the mirrors. The 1 meter flat to flat hexagon was a natural successor to the original 1 meter round and importantly also matched comfort levels for handling and the tooling sizes at both optical fabricators and coating vendors. The 1-meter size also matched well to thicknesses of interest and mounting schemes of reasonable complexity.

The nominal 52mm thickness was established by several criteria. Reasonable thermal equilibration without supplemental mirror cooling systems could be expected, particularly when the starting temperature of the entire telescope could be controlled via the facility air conditioning and control system. The substrate can be mounted on a 9 point Hindle arrangement with approximately .3 micron residual print-through at the optimal Hindle mount points at the use elevation vector. It was decided that these errors would be removed via optical figuring, providing correct optical figure in use. All segments would be tested on an operational mount at a single 55 degree elevation and analysis showed acceptable difference in figure when installed at top or bottom positions in the array. The pointing vectors of top segments are at a 45 degree elevation and the bottom are at a 65 degree elevation by the nature of the spherical surface. Figure 7 shows the finite element model of half a segment on the 9-point support. (10)

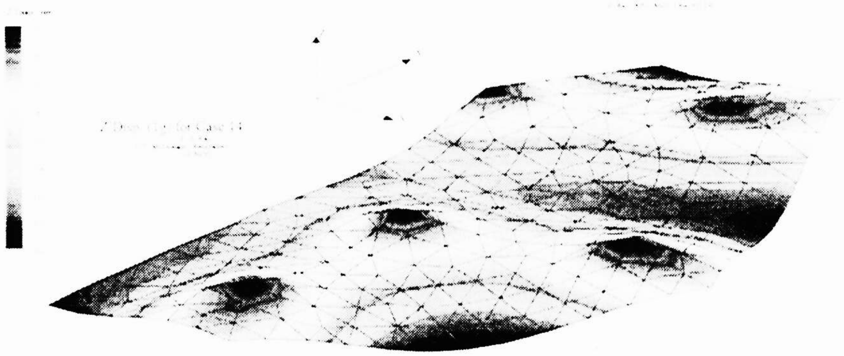

Figure 7: Finite element model showing gravity induced deflection of segment front surface on mount

Schott Glass, Duryea, PA (Mainz, Germany) won the contract to provide the substrate material. Oversized hexagonal shapes were provided with flat top and bottom surfaces. Ninety-six segments were provided (5 specified for operating spares) over a 1.5 year span. The volume of glass in easy identical shapes was a big factor in realizing the $645,000 price tag but so was limited characterization and material testing. For each bulk section of material (3 to 4 segments) a top and a bottom CTE sample were used to verify overall tolerance as well as to predict gradients within the material. All substrate orientations were maintained to insure any CTE gradients always went in the same direction front-to-back to ensure radius matching.

4.3 Optical Fabrication: Identification of an accurate, rapid, and cost effective optical fabrication process for segments was fundamental to the success of the HET primary mirror. Limiting mirror types to a single configuration is the single biggest cost saving feature in mirror fabrication. The HET project provided an operational mount for the testing and the mirror substrates. The optical fabricator then performs the final shaping and fabrication to final optical quality when mounted on the operational mount at the nominal use elevation. Throughout the mirror design period, significant interaction was maintained with potential vendors to provide and accept inputs that maximize the design and development plans to current industrial capabilities. This interaction also provided the opportunity to suggest potential techniques of interest to the project. The key optical fabrication requirements are summarized in Table 2 below.

Parameter	Requirement
Optical Figure	Spherical, R=26,165 mm +/- 10 mm
Radius Matching	All segments to +/- 0.5 mm
Figure Error	0.052 microns RMS, mounted on 9 point support, with optical axis at 55 elevation angle
Clear Aperture	Out to 4 mm from the physical edge
Surface Roughness	Less than 25 Å RMS

Table 2. Critical Optical fabrication Requirements

Eastman Kodak was awarded a $1.6 M contract to provide the final shaping and optical fabrication of the HET mirror segments on the basis of cost and risk, both being low. The fabrication process has four key features which contribute to the success of the fabrication effort.(11) The first is the mass production and scheduling to allow the segments to flow through the shop in conventional process steps as both a significant focus of effort and as fill work. Second is the use of a spherical planetary polisher that excelled at polishing the surface and controlling the radius of curvature of the segment. Surfaces were routinely smooth to 5 Å so the risky step of measurement with a heavy Chapman instrument resting on the optical surface was reduced from every segment at several locations to random segments. Third is the use of the ion figuring chamber which was used on every segment one to four times depending on several fabrication factors. The fourth key feature is the test fixture. The use of a transmissive fused silica test sphere in close proximity to the test surface results in a very simple, accurate, and repeatable metrology stand. The test plate required some significant initial characterization but provides a long term reference as well as enables a short optical path test with very repeatable results. The use of a test sphere made simple the requirement to maintain close tolerance on radius of curvature between the many segments.

Segment Supports: Initial development of the concept for segment support was performed by Eastman Kodak and the HET Project Team. The approach for axial support was based on a Hindle mount, with 3 tetrahedrons providing a total of 9 interface points to the back surface of the mirror. Invar buttons are epoxy bonded to the mirror back surface providing semi-kinematic mounting for each tetrahedron and spreading the support force over the approximately 16 mm diameter of the buttons. The 3 tetrahedrons were in turn mounted via a ball and socket at their center of mass to compound lever systems which allowed them to be moved independently in an axial direction to control mirror segment pointing and piston positions. A central blade flexure relays lateral loads to a stiff center pin, allowing axial motion but eliminating lateral loads on the Hindle mount points.

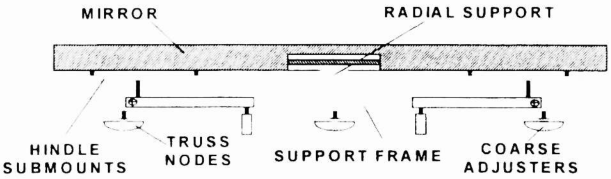

Figure 8. Conceptual layout of mirror support.

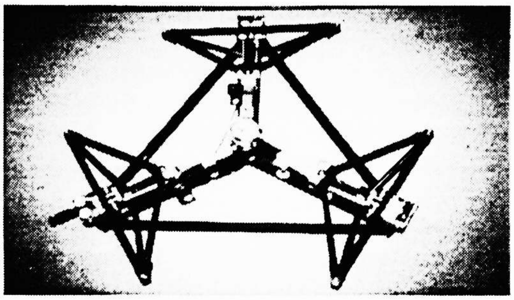

Figure 9. Photo of production mirror mount.

Detailed drawings and a prototype mount were developed by the HET Team and provided to Kodak for initial test of segments. Testing of the mount at Kodak was fairly straightforward, but required some effort. Design of a production mount was performed by Sebring Design in Townsend, Massachusetts and focussed on reducing part count and manufacturing operations as well as selecting manufacturing approaches to minimize cost and complexity. The result was use of formings, castings, commercial components, and machined parts. Components were contracted, purchased, and assembled by the HET Project Team.

Tests of mounts at Kodak have revealed that the mounts are interchangeable, exhibit errors within the error budget tolerance for mount induced error, and are tolerant of a reasonable amount of abuse and neglect without degraded performance. The compound lever provides 11.9:1 reduction for a suite of motor micrometers used for mirror actuation and increase axial stiffness to resist wind buffeting. Installation of mirrors to mounts and modules to the primary array was performed by the

HET Team. Mirror modules can be installed or changed quite rapidly, ranging from 1 hour to 2.5 hours depending on location in the array.

Mirror modules interface to the primary mirror truss via coarse adjusters which allow for lateral positioning and coarse piston and tip/tilt adjustment. During mirror installation it was found that a new mirror could be aligned in about 15 minutes and that the coarse adjusters provide granularity of approximately 0.01 mm in piston. A simple spherometer is used for initial segment alignment along with subjective observation of laser return from the center of curvature. The total cost of mirror mounts was approximately $350,000 including all components, design development contracts, and some HET labor.

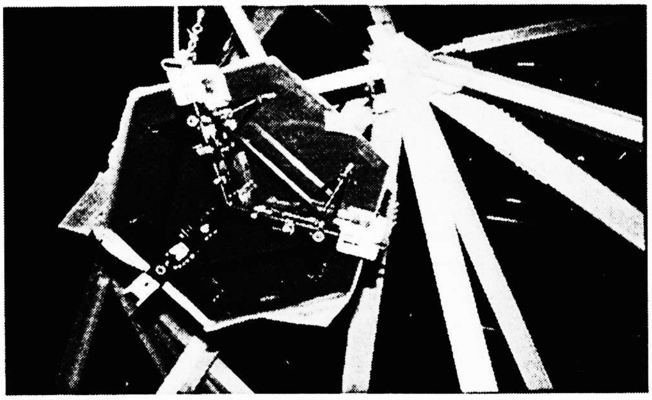

Figure 10. Mirror #1 being installed in HET.

Segment Positioning System (SPS): The SPS system provides the motion control system for fine positioning of all the mirrors in the array. The SPS includes 3 linear actuators per mirror, control electronics to administer motion requests to the actuators, a computer system to orchestrate all moves, and a power system to energize the system components. Definition of the actuator requirements was done in conjunction with the segment support hardware development. Anticipating the use of readily available motor micrometers the segment support hardware includes a lever system to boost the axial stiffness of the full assembly. The support geometry and the desire to make pure tip (about X axis) and tilt (about Y axis) motions better than the 0.062 arcsecond alignment tolerance defines the required actuator resolution of 25 nanometers. Total stroke of 1.5 mm is specified to allocate some range for fine initial alignment and some for bulk temperature (seasonal) changes in the truss. The system was also specified for performance in keeping with very low bandwidth operation. Expecting thermal algorithm based corrections to be commanded on the order of once in 15 minutes the system was specified to handle a nominal 100 step move of all actuators, from dormant state back to dormant state, in 3 minutes. The dormant state refers to the further requirement that all components connected to the truss be operated in modes where power dissipation to heat is only occurring during the intervals that motion is being requested. All system components always powered are to be confined to thermally isolated igloos in discrete locations of the telescope.

The system was developed as a joint effort between TS Products (Post Falls, Idaho) and HET project software engineers. TS Products supplied the 273 actuators, controllers, interconnect and communication hardware, and some rudimentary control software for $343,000. The final control software with interfaces to actuator controllers and telescope systems was developed by the HET.

The actuators are TS Products' model 2200 linear devices driven through gears by a stepper motor. The actuators are only operated at the natural detent positions defined by the motor windings so hold currents are not required. Each actuator has nominally 25 mm of travel at a resolution of 0.218 microns per step. In the support hardware the actuators are limited to roughly 100,000 steps so the available positioning at the mirror through the lever is 1.83 millimeters of travel in 18 nanometer steps. Given the support geometry this translates into +/- 600 arcseconds of tip motion, +/- 700 arcseconds of tilt motion at the mirror with resolutions of 0.021 arcseconds in tip and 0.014 arcseconds in tilt. The model 2200 actuators have built in home /limit switches with better than 0.3 micron repeatability but do not have encoder feedback. The encoders are not necessary for general stepper motor control but they have been missed during the debug stage of development.

A programmable controller, Model MC-602, manufactured by Olsson Research operates each actuator. These dual channel controllers provide a daisy-chained RS232 bus for ASCII communication with individual controllers. In the HET the controllers have been divided up into 5 communications banks with no more than 30 controllers (60 actuators / 20 mirrors) per bank.

The system is controlled with a 486 PC computer running Windows 95, with 8 communication ports. The software is written with Microsoft's Visual C/C++ version 2.00 programming environment. The primary tasks for the software are communication with upper level systems, determining the command sequence to the controllers, managing and consolidating the controller communications, powering only those banks where movement is requested, position and other parameter house keeping, motion progress and many other chores necessary to make the system robust. A simple engineering interface is provided at the SPS which allows individual mirrors to be configured and moved as required.

Center of Curvature Alignment Sensor (CCAS): Based on technology developed in collaboration with the USAF (12) a center of curvature sensor was proposed by W.J. Schafer Associates of Rome, N.Y. This sensor is a lateral shearing interferometer which utilizes polarized light and matched Wollaston prisms to achieve lateral shear, interfering optical returns from adjacent segments to form fringe patterns. The instrument features two channels, each with a different direction of shear, one 60 degrees with respect to the other and operates by judging relative tilts from one segment to the next along two different paths, hence accounting for both tip and tilt.

Resolution is further enhanced by phase shifting each channel, with waveplates used to create one unshifted and 3 (¼, ½, ¾,) wave shifted interference patterns simultaneously. Each phase shifted interferogram from both channels are imaged by high speed (1/1000th sec) ccd cameras and evaluated by conventional "4 bucket" algorithms. An additional ccd camera images the front entrance plane of the instrument providing images for coarse alignment of segments, bringing the total number of cameras in the instrument to 9.

Operation for tip/tilt is achieved using a single HeNe laser source, for piston measurement multiple laser diodes of different wavelength are used and the contrast function determined by the beat frequency used to determine phase or piston errors. The instrument features a scanning device which can vary path length of the reference arm to measure piston error within a 10 micron window. This aspect of the device has been less functional than desired, though the optical error budget allowance for piston error can be met and maintained with simple spherometer measurements and position maintenance algorithms within the segment positioning system software.

Interferograms for tip/tilt sensing are analyzed automatically via provided software routines. Current problems with HET mirror alignment have their root in range vs resolution trades. The CCAS is designed to meet stringent alignment tolerances (.005 arc sec) and hence has substantial precision. The capture range, however is limited to 0.36 arc sec, which does not serve the need for coarse alignment on start up. This has led to substantial development by the HET Operations Team of alternative coarse alignment tools and consideration of additional systems for mirror set-up and maintenance. The CCAS was delivered for a total cost of $275,000.

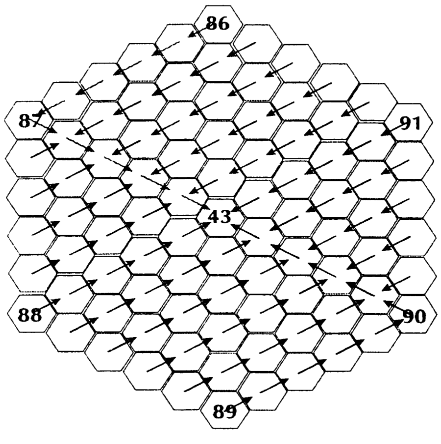

Figure 11. Sequence pattern for mirror tip/tilt evaluation by CCAS instrument.

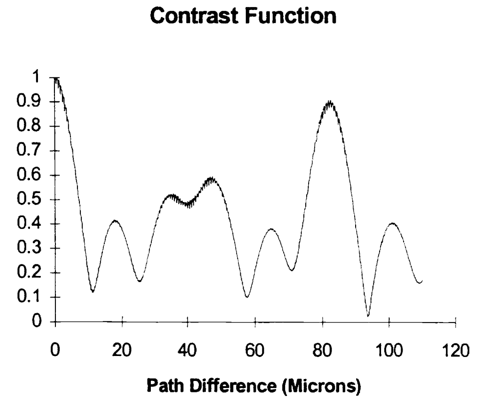

Figure 12. Contrast function for wavelength laser diode source.

5. CURRENT DEVELOPMENT

General Status: Currently 80 of the 91 mirror segments have been polished, coated, and placed in the truss. The remaining 11 mirrors are at Kodak having their final polish done. They are expected to be finished with the Denton FSS-99 coating and be on site by late April 1998. The operations team is spending most of their time developing an understanding of how to properly align the mirrors in tip, tilt, and piston and how to maintain that alignment for the required time periods. Additional tools are being built to aid in this effort and to provide the automated operation required for routine science operation. A number of attempts to do science with the telescope provided valuable information in understanding what critical factors require the most work in order to get the system operational.

Thermal data from the truss thermal sensor system are being collected on a routine basis and are being analyzed in order to understand the thermal behavior of the truss. A low-order thermal correction algorithm, based on purely theoretical principles, is being put in place to provide initial temperature compensation of the truss. This algorithm assumes only uniform temperature changes in the truss and a temperature differential between the front and back surfaces of the truss. Further refinements and higher order corrections will be put into place to account for local heating/cooling of the truss as additional temperature and pointing data are acquired.

The goal of the operations team is to provide 50% science time with all mirrors in place by late summer 1998. The team is rapidly gaining experience in running the telescope (13) and in doing the mirror alignment. As of early 1998 the system is able to achieve a FWHM spot of 1.5 arcseconds with 21 mirrors. This alignment can be maintained to within 25% if the temperature of the truss changes by no more than the specified 0.5C per hour.

6. SUMMARY

The HET Primary Mirror represents a significant departure from prior astronomical mirrors in that it provides significant cost savings and an engineering approach which can be extrapolated to even larger sizes. The total cost of contracts and purchases for the primary mirror system was $3.8 million (including $110,000 for optical coating), or about $50k per square meter. Development to date has been fairly straightforward, with few surprises in construction. Operation is proving somewhat more difficult and it is expected that several years of ongoing optimization concurrent with astronomical research will be required to attain optimum performance. It is worth noting that the alignment of primary mirror segments has always been identified as the highest risk area of the HET and that an open loop approach to position control was taken as a direct consequence of cost. Strategies for optimization include:

1. Implementation of full environmental controls to minimize thermal excursions of the primary mirror system hence maintaining the system within the elastic range of expansion and contraction of the truss and mount systems.
2. Implementation of thermal based correction of segment position based on temperature measurements and closed form solutions for bulk material based radius change for the steel truss and "bimetallic" bending driven by axial thermal gradients in the truss.
3. Implementation of finite element model based correction of segment position based on distributed temperature measurements throughout the truss.
4. Implementation of neural net-based algorithms capable of "trained" responses in mirror position based on distributed temperature measurements.
5. Development of an automated intermediate alignment device, perhaps Shack-Hartmann based, which is capable of rapidly aligning segments to within the capture range of the CCAS sensor.
6. Procurement and installation of a capacitance based segment-to-segment position sensing system capable of maintaining segment alignment over long periods of time well within capture range of the CCAS sensor for periodic calibration.

The first two solutions are relatively simple and are being implemented as this paper goes to press. Solution 3 will be evaluated with prepared tools when more segments are brought under control to provide a higher resolution metric of the truss dimensional response. Initial investigations into the last solution indicate that current capabilities with capacitance sensors and control methodology might yield a system for the HET for roughly $350,000. In combination with the existing CCAS, the coarse alignment tools currently in development, and future alignment techniques, the edge sensor system can be expected to maintain alignment of the array for a minimum of one day and potentially several weeks. With demonstrated performance on Keck, developments from NASA's segmented mirror initiatives, the relatively low system cost, and the enormous advantage of position feedback, an edge sensing system may well be the most pragmatic approach to support development work and to rapidly achieving the ultimate mirror performance objectives.

7. ACKNOWLEDGEMENTS

The authors wish to thank the following individuals for their many valuable contributions to the mirror development. Many people contributed to the success of this effort, and we apologize for the inevitable omissions:

HET Project Team:
Lawrence Ramsey
George Barczak
J. Fred Harvey.
Larry Long,
Al Mitchell
Joan Sage
Michael Steiner
Stephen Medwadowski
William Gressler
John Booth
Jim Blum

HET Operations Team:
Niall Gaffney
John Glaspey
Craig Nance
Grant Hill
Matthew Shetrone
Francois Piche
Brian Roman
Vickie Fowler

8. REFERENCES

1. Ramsey, L. W., Sebring, T. A., and Sneeden, C., "*Spectroscopic Survey Telescope Project*", S.P.I.E. Vol. 2199-05, Advanced Technology Optical Telescopes V, March 1994.
2. Booth, J. A., Ray, F. B., and Porter, D. S., "*Development of a Star Tracker for the Hobby-Eberly Telescope*", S.P.I.E. Vol. 3351, Telescope Control Systems III, (in press).
3. Sebring, T. A., Booth, J. B., Good, J. M., Krabbendam, V. L., and Ray, F. B., "*Design and Status of the Spectroscopic Survey Telescope*", S.P.I.E. Vol. 2199-52, Advanced Technology Optical Telescopes V, March 1994.
4. Gaffney, N. I., and Cornell, M. E., "*Planning and Scheduling Software for the Hobby-Eberly Telescope* ", A. S. P. Conference Series, Vol. 125, p. 379, 1997.
5. Ray, F. B., "*SST mirror truss: Geometry and component layout*" HET Tech files, TR-930507, October 14, 1993.
6. Gressler, W. J., "*HET Telescope Error Budget*", HET Tech Files, WJG-94-005, April 1997
7. MacQueen, P. J., *SST Optical Report – Part One*, Revision A
8. Medwadowski, S. J., "*Structure of the Spectroscopic Survey Telescope*", S.P.I.E Vol. 2199-33, Advanced Technology Optical Telescopes V, March 1994.
9. Ray, F. B., "*Automated Design Technique for Steel Trusses Supporting Close-Packed Hexagonal Mirror Segment Arrays*", S.P.I.E. Vol. 2199-95, Advanced Technology Optical Telescopes V, March 1994
10. Ray, F. B., "*Solid finite element analysis and optimization of the SST hexagonal segment for all regions of the primary mirror*", APG TR-930415, April 1993.
11. Pileri, D., Krabbendam, V. L., "*Hobby Eberly Telescope Primary Mirror Fabrication*", S.P.I.E. Vol. 2536, Optical Fabrication and Testing, July 1995.
12. Klumpe, Herbert W.; Lajza-Rooks, Barbara A.; Blum, James D., 1991, "*Absolute Phasing of Segmented Mirrors Using the Polarization Phase Sensor*", S.P.I.E. Vol. 1532, Analysis of Optical Structures, Donald C. O'Shea, Ed.
13. Ramsey, L. W., Adams, M. T., Barnes, T. G. III, Booth, J. A., Cornell, M. E., Gaffney, N. I., Glaspey, J. W., Good, J. M., Fowler, J. R., Kelton, P. W., Krabbendam, V. L., Long, L., Ray, F. B., Ricklefs, R. L., Sage, J., Sebring, T. A., Spiesman, W. J., Steiner, M., 1998, "*Early performance and present status of the Hobby-Eberly Telescope*", S.P.I.E. Vol. 3352, Advanced Technology Optical/IR Telescopes VI, (in press).