The Hobby-Eberly Telescope Completion Project

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ABSTRACT

The Hobby-Eberly Telescope (HET) is a fixed-elevation, 9.2-m telescope with a spherical primary mirror and a tracker at prime focus to follow astronomical objects. The telescope was constructed for $13.9M over the period 1994-1997. A number of telescope performance deficiencies were identified and corrected following construction. Remaining problems included: 1) Dome seeing, 2) inadequate initial mirror segment alignment accuracy, and 3) mirror segment misalignment with time. The HET Completion Project was created in May 2001 to attack these problems and to identify and solve the next tier of problems. To address dome seeing, large louvers were installed and in operation by May 2002. Efforts are also underway to eliminate or suppress heat sources within the dome environment. To address segment alignment accuracy, a prototype Shack-Hartmann device, the Mirror Alignment Recovery System (MARS), was built and is in routine use at HET. The Segment Alignment Maintenance System (SAMS) is in early operation and has markedly improved telescope performance. Two Differential Image Motion Monitor (DIMM) telescopes were brought into regular operation in July 2001 to quantify atmospheric seeing at HET. As these improvements have been implemented, telescope image quality has improved significantly. Plans are in place to address additional performance issues.

Keywords: Hobby-Eberly Telescope, HET, dome seeing, dome ventilation, MARS, mirror alignment, Shack-Hartmann, SAMS, edge sensors, DIMM

1. INTRODUCTION

The HET (Figure 1) is a 9.2-meter tilted Arecibo-style telescope with a segmented primary mirror and moving star tracker at prime focus. Its design was a prototypical approach to the construction of a large, low-cost, telescope optimized for spectroscopy. Following construction, shakedown, and initial commissioning, the telescope was increasingly used in science operation, but continued to have persistent performance problems in the areas of image quality and efficiency. In the six months prior to June 2001, the telescope was in science operation 48% of the available observing time, with a mean telescope image quality of 2.1 arcsec FWHM. Many of these problems had to do with limited funding available at the time of design and construction. The degraded image quality constrained the types of science that could be pursued with the telescope.

In May of 2001, HET and McDonald Observatory management determined to accelerate progress in fixing these problems. The HET Completion Project was created, with increased manpower and funding, and tighter focus on key telescope subprojects. This paper describes the activities undertaken during the recently completed first year of the Completion Project (Phase I), the current status of the HET, and plans for the next 18 months (Phase II).

Figure 1: HET at sunset, showing new ring wall louvers.

2. BACKGROUND

2.1. HET Description and History

The HET was funded and built by a consortium of five universities, the University of Texas at Austin, the Pennsylvania State University, the Ludwig-Maxmilians Universität München, the Georg-August-Universität Göttingen, and Stanford University. Descriptions of the telescope[1], its operation[2], scientific instrumentation[3,4,5,6], commissioning experience[7,8], and early science results[9,10] may be found at the indicated references, but a brief description of its operation and history is included here for the reader's convenience.

The fixed-elevation telescope employs a spherical segmented primary mirror supported by a steel truss as an essential part of the telescope's low-cost, Arecibo-style design concept. All 91 segments are identical regular hexagons. The unique design of the HET allows the primary mirror to remain stationary during an observation; it can be repositioned in azimuth between observations to access different areas of the sky. The mirror has a constant zenith angle of 35 degrees, and thus always has the same orientation with respect to gravity. Images of astronomical objects are acquired and followed across the mirror array at prime focus for up to 2.5 hours by means of a tracking device mounted atop the telescope structure. This unusual mode of operation is somewhat difficult to visualize, and the reader is referred to Figures 2 and 3, below, for a more visual description.

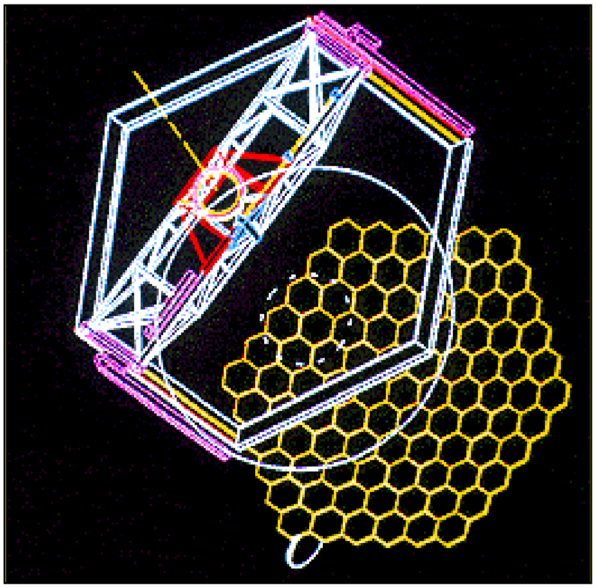

Figure 2: Telescope operation. (Tracker payload and telescope structure are not shown for clarity.) The telescope is pointing south and acquiring an object in the east. Note the large circle on the primary mirror, delineating the telescope entrance pupil on the primary.

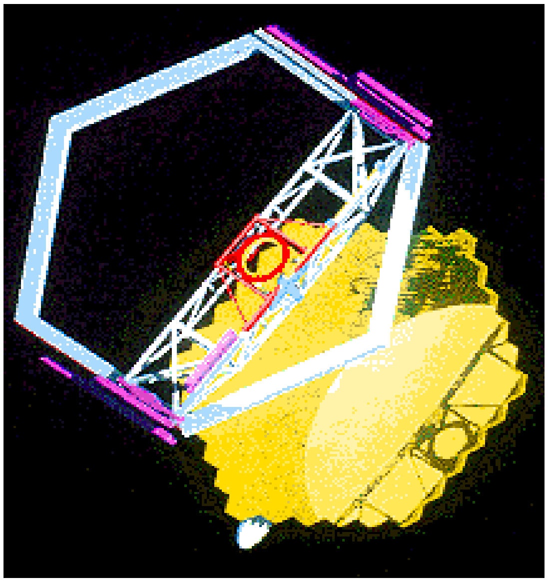

Figure 3: Telescope has completed track begun in Figure 2. Note the illuminated active pupil on the primary mirror. Object is now well past the meridian in the west.

The design simplifies the mirror support problem and significantly reduces the initial cost of the telescope. The construction cost of the telescope was $13.9 M, about 15% of the cost of fully steerable telescopes of comparable size. Design and construction time was approximately five years. HET first light was achieved in December 1996 with seven mirror segments collecting and focusing light through a test optical corrector. Installation of the design corrector (February 1999) and first facility instrument, the Low Resolution Spectrograph (LRS), (April 1999) were followed by completion of primary mirror segment installation in May 1999. HET currently is in science operations about 75% of the time, with the remaining time used for engineering and instrument commissioning activities.

2.2. Telescope Problems

HET was an ambitious project from its inception, aspiring to build a very large telescope comparatively inexpensively by deliberately limiting some typical telescope capabilities, such as full steerability, to fund an increased primary mirror size. Perhaps not surprisingly for an innovative design on a limited budget, the telescope has had its share of problems. While many telescope subsystems functioned well from the beginning, several subsystems, such as the Primary Mirror Control system (PMC) and the tracker[11], were not fully debugged prior to formal commencement of science operations in October 1999. The tubular steel primary mirror truss proved to be insufficiently stable to maintain segment alignment passively for hours at a time. An edge sensor system to stabilize mirror alignment had not been included in the original HET design concept.

The Center of Curvature Alignment System (CCAS)[12] for fine initial alignment of the primary mirror array never worked to specification and eventually had to be abandoned for a new alignment system. In the interest of getting the telescope up and running as quickly as possible, heat sources within the dome were not adequately dealt with during the commissioning and early operations phases. Even with these heat sources temporarily turned off, dome seeing was poor, as the dome exhaust fans proved inadequate to the task ventilating the dome sufficiently.

Finally, an end-to-end optical test for the 4-mirror Spherical Aberration Corrector (SAC) had never been devised, nor had a null test for one of its mirror elements, M5. This mirror was fabricated using precision profilometry only. The SAC mirrors were assembled and aligned on a best-effort basis using mechanical, not optical, techniques.

3. HET COMPLETION PROJECT, PHASE I

3.1. Project Initiation and Goals

In the spring of 2001, we created a special project to focus the engineering effort more tightly on key tasks that would directly improve telescope performance. We chose the name "Completion Project" to reflect our perception that the telescope still lacked elements essential to meeting performance specifications. Funding and manpower for the project were made available primarily by the University of Texas McDonald Observatory, with some additional funding from the Pennsylvania State University. The goal of the Project was to improve, complete, and where necessary create those subsystems necessary to achieve the original telescope specifications[13].

3.2. Planning

We determined four key problem areas to attack in Phase I of the Project: 1) Dome seeing, 2) poor initial segment alignment, 3) segment alignment drift (already being addressed with SAMS project), and 4) characterization of site seeing. Solving these problems would help pave the way to diagnose and fix other areas of telescope performance, as noted below:

- Dome Seeing: A seeing "tiger team" had been formed in the spring of 2001 to determine the causes and potential solutions for suspected poor dome seeing. After a review of the literature and existing site data, the answer was clear: Ventilate the dome enclosure, and address the known problems of unsuppressed active and passive heat sources within the dome. The team also recommended establishing permanent site seeing monitoring (DIMMs) near HET to determine realistic image quality goals for the telescope.
- Poor initial primary mirror alignment: Poor initial primary mirror alignment (average 1.2 arcsec EE50% aligned stack size at CCAS, as bad as 1.8 arcsec EE50% some nights) limited on-sky image quality on the best observing nights. The newly debugged CCAS instrument had proven unable to capture and control most of the mirror segments under normal environmental operating conditions. It was essential to improve initial mirror alignment to the point that it would not limit on-sky image quality. A new alignment device was needed.
- SAMS: We began the SAMS project in October 1998 following the solid segment mount investigation[14,15], when it had become apparent that the primary mirror truss lacked the necessary stability to maintain segment alignment for several hours. We included SAMS in the Completion Project scope, as it was critical to achieve the eventual specification performance of the telescope. In addition, more precise Hartmann testing of the SAC depended on a stable primary mirror array.
- Site seeing characterization: Without a real-time seeing monitor with which to compare telescope image

quality, it was difficult to assess specific causes of poor image quality on a particular night. At the recommendation of the seeing tiger team, we included nightly operation of a local DIMM at HET as a Completion Project goal.

3.3. Dome Ventilation System (DVS)

The task of ventilating the dome and suppressing heat sources within it was broken down into sequential sub-tasks, the first of which was the ventilation of the HET ring wall. This promised to deliver the biggest “bang for the buck”, ventilating a large surface area using a proven Kitt Peak louver design. A site visit was made to the KPNO 4-m telescope in June 2001, and confirmed Kitt Peak’s positive experience with their louver design.

3.3.1. Ring wall Ventilation System (RWVS)

The HET enclosure was originally designed for forced ventilation by means of 6 ventilation fans distributed radially around the ring wall. Poorer-than-expected fan performance (12 dome air changes per hour instead of the original design requirement of 20), and the lack of dome insulation contributed to poor dome seeing conditions. This was demonstrated by interferometric images taken from the CCAS instrument, and subsequently by pupil images from the MARS alignment instrument. Analysis indicated that air flushing velocities necessary to maintain the structure/primary mirror temperature to within 0.4^{o}C of ambient temperature to minimize seeing could not be generated by fan systems of reasonable size.

The louver design incorporates 12 pairs of custom-built louver modules, each 4.8 m wide x 5.3 m high, and two individual modules half as wide (see Figure 4). A detailed description of the RWVS project may be found elsewhere in these proceedings[16].

Figure 4: Louver design (August 2001) and as-installed (May 2002).

RWVS was fully implemented in less than one year, from June 2001, when detailed design was initiated, to May 2002, when the project was completed. An innovative louver crane was designed that used the rotating telescope dome as its translation axis, and a commercial hoist for lifting. The crane is shown in operation in Figure 5, below. The savings over renting a crane was approximately $100,000, and eliminated additional schedule pressure during periods of marginal weather conditions.

Louvers were put into operation as they were installed, beginning in February 2002, and improvements in the image quality were noted both at the alignment instrument and on-sky (see Figure 11).

The ventilation design implemented opens approximately 58% of the ring wall, in order to achieve natural ventilation of 22 air changes per hour at the minimum design wind velocity of 3.5 mph. The next phase of enclosure ventilation will open approximately 8% of the dome. Ventilation louvers on the ring wall promote thermal equilibrium of the primary mirror and concrete pier, while louvers in the dome will supply flushing winds at the level of the tracker/secondary assembly located at the top of the telescope structure. Insulation and recoating of the dome will minimize radiative cooling and greatly increase the efficiency of air-conditioning during the day. In addition, as part of the overall thermal management strategy, active and passive heat loads interior and exterior to the enclosure will be enclosed and ducted to an Eastward location about 100 meters from the facility.

Figure 5: Louver crane in operation, preparing to install second louver module in the north side of the ring wall.

3.3.2. In-dome active heat source suppression

The desirability of eliminating or minimizing the effect of active heat sources within a telescope dome has long been known to amateurs and professionals alike. This is particularly true of sources directly in or near the telescope optical beam. For a prime focus telescope such as HET with several detector electronics packages in the beam, suppressing such heat sources can be more difficult than with a conventional telescope.

There are three major sources of active heat generation within the HET dome: The tracker payload electronics, the electronics bay beneath the primary mirror truss, which houses primarily tracker drive electronics, and the JLG person-lift located just outside the telescope pier. Each of these problem areas is being addressed during the course the Completion Project.

The tracker payload electronics area is the most difficult to cool, not only because it sits in the optical beam 20 m above the dome floor, but also because it translates and rotates in all six degrees of freedom to track objects across the 3.8-m diameter focal sphere. Efforts to get the telescope payload (Prime Focus Instrument Platform (PFIP), SAC, and LRS) operational in 1998 and 1999 overwhelmed the important task of cooling this area. Early attempts to exhaust heated air from this region ended in failure due to an underpowered exhaust system. A new system has been designed (see Figure 6) and is currently being installed with much larger ducting and exhaust fans. It will route the heated air off the telescope, outside the dome, and away from the facility. Completion of this system is expected by the end of September 2002. It will eventually be replaced by an ethylene glycol/water (EGW)-based liquid cooling system.

The large electronics bay under the mirror truss will tie into this air extraction system in the short term. By the end of the Completion Project, we anticipate replacing both on-telescope air extraction systems with EGW-cooled heat exchangers, which will obscure the optical beam less, do a better job of heat removal, and be less cumbersome that the air ducting.

The JLG is a large nighttime heat source when it has been run within a few hours of dome opening

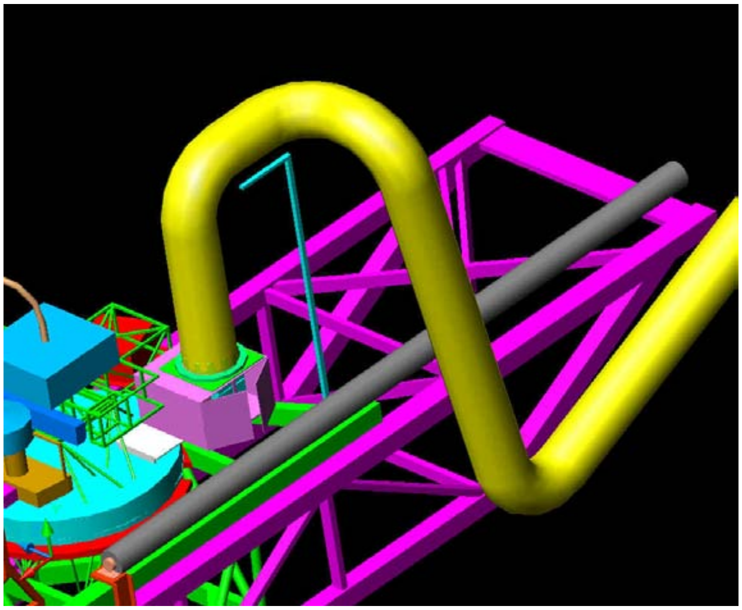

Figure 6: Payload electronics heat extraction design

time. A flexible ventilation duct with a rotational mechanical interface to accommodate JLG rotation was installed recently to remove this heat load from the dome. Figure 7 shows the system in initial operation. The ducting has since been suspended from the dome wall to facilitate foot traffic in this area.

Figure 7: Early operation of JLG ducting

The ducting exits the telescope dome through one of the formerly used exhaust fans at the left side of the picture. The open dome louvers may be seen in the upper portion of the picture.

3.4. Mirror Alignment Recovery System (MARS)

The original HET alignment instrument, the CCAS, employed a coarse alignment scheme using laser light from the Center of Curvature (CoC) to generate returned laser spots on an imager, which was also at the (folded path) CoC. Its fine alignment scheme used a Twyman-Green polarization shearing interferometer to align each segment to 0.06-arcsec rms. The coarse alignment technique was refined by the HET Operations staff until stack quality plateaued around 1.2 arcsec EE50% at the CCAS faceplate. The technique was extremely labor-intensive and telescope operator-dependent, with some telescope operators obtaining better stacks than others.

A concentrated engineering effort was made prior to the commencement of the Completion Project to make the interferometric side of CCAS functional[17]. The effort eventually succeeded in making the instrument “lab functional”, but the interference fringe-based method was highly susceptible to seeing conditions, and the capture range of the fine alignment side of the instrument remained too small (0.36 arcsec) for operational use.

In March of 2001 we discussed the alignment problem with Gary Chanan of UC/Irvine. He suggested investigating a Shack-Hartmann device mounted either at the CCAS location, or near corrected prime focus on the telescope payload. Chanan also proposed a workable reference mirror scheme to identify aligned segment target locations. This discussion, and the failure of the debugged CCAS instrument to perform adequately under routine observing conditions led to agreement with Allan Wirth of Adaptive Optics Associates, Inc. (AOA) in May 2001 to develop a CoC-based Shack-Hartmann system.

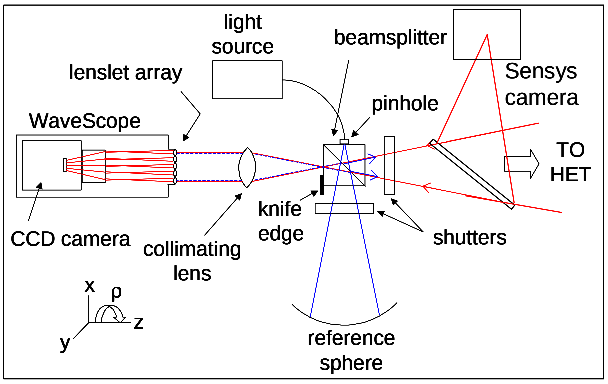

Figure 8: MARS-POC schematic, top view. Light expands from a fiber-fed pinhole on the side (top here) of the beamsplitter cube, reflects down to and illuminates the HET primary, returns to focus at the primary's center of curvature on the back (left here) side of the cube, is collimated by a lens, encounters the lenslet array which has each lens matched to an HET segment, then is focused and imaged onto a CCD camera. Another leg contains a spherical reference mirror for calibration, shown at the bottom of this schematic. The thin beamsplitter to the right provides an image of the entire mirror stack returned from the HET to the Sensys camera. (From M. Wolf et al.)

Figure 8 is a schematic diagram showing how MARS works. It is based on the AOA WaveScope Shack-Hartmann wavefront sensor. We included a pellicle foreoptic to divert the beam to an imager (currently the SenSys camera shown), so that we can continue to measure the stack size at the CoC.

The instrument is coarse-aligned to the HET primary mirror by eye using retro reflections of the MARS white light source off the primary mirror. Fine alignment is accomplished by using the WaveScope software and the WaveScope itself, as though the primary mirror were the optic under test.

MARS-aligned images at the CoC typically average 0.9 arcsec EE50%, vs. 1.2 arcsec EE50% with the previous CCAS method. The majority of this image size is thought to be due to dome seeing and segment figure errors, as the typical single segment image size is about 0.6 arcsec EE50%.

MARS has turned out to be extremely useful in debugging SAMS, as we can now monitor the drift rate and direction of individual primary mirror segments under varying conditions. Using the CCAS instrument for the seven-segment Sub-Array Test in the SAMS development phase, we had great difficulty understanding what was happening to individual segments in initial alignment. MARS allows the determination of individual segment tips and tilts while the array is aligned, and the segments spots are otherwise lost inside a larger, focused composite image.

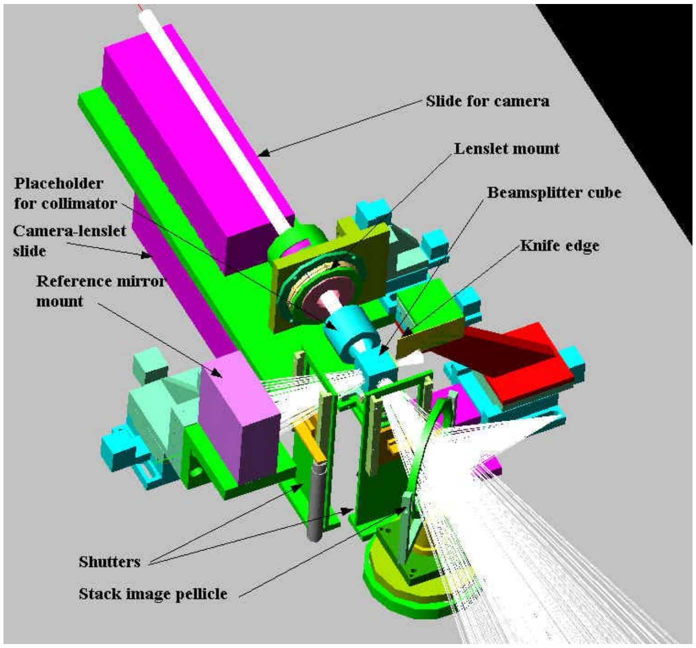

Figure 9: Final version of MARS instrument, concept drawing

The MARS currently in use on the telescope is a Proof of Concept (POC) instrument. It was designed and built in 4 months to exploit a window in the telescope engineering schedule in the summer of 2001. While the POC instrument performed well beyond expectations, and has been upgraded over the past nine months, a final version of MARS with enhanced features is under construction. The new design is shown in Figure 9. It features more robust optomechanical mounts, a larger, faster detector with higher dynamic range, and better data handling than the POC version.

Focusing the instrument at the correct radius of curvature has turned out to be unexpectedly time consuming and difficult task, accounting for about half the total time it takes to align the primary mirror. The new MARS will feature three focusing methods, including a two-mode knife-edge test (fast and slow), and an image-based autofocuser.

A Linux version of the AOA WaveScope software will be used for instrument control and analysis.

We project that the final MARS instrument will become operational by the end of 2002, and should improve stacking accuracy perhaps 30%, and stacking efficiency by about 50% compared with current operational performance.

3.5. Segment Alignment Maintenance System (SAMS)

HET first light was achieved in December 1996 with just seven primary mirror segments. In the conventional sense, this was in fact "engineering" first light, and demonstrated basic acquisition, pointing, and tracking capabilities of the telescope. Soon after this milestone, segment "destack" was observed, in which the group of seven return spots from the CCAS laser began to separate after as little as an hour or two after being stacked, or aligned. As more segments were added farther from the mirror truss center, this phenomenon was observed to occur even more quickly. A temperature dependency was also established, with destack roughly proportional to temperature gradient. Once it was conclusively determined that this undesirable segment behavior was associated with the mirror truss and not individual segment supports, we began what became the SAMS project to outfit the primary mirror array with a control system to hold it in alignment.

We reported on the SAMS early development phase over two years ago[18]. At that time, no hardware had been built, and a contract had recently been let to the team of Marshall Space Flight Center, Huntsville, AL and Blue Line Engineering, Colorado Springs, CO. Since then, the system has passed all development milestones, including an on-telescope seven-segment sub-array test in December 2000[19]. The final system was installed on the telescope in early fall 2001[20]. SAMS has been operating for 10 months with few service interruptions since it went into operation 13 October 2001.

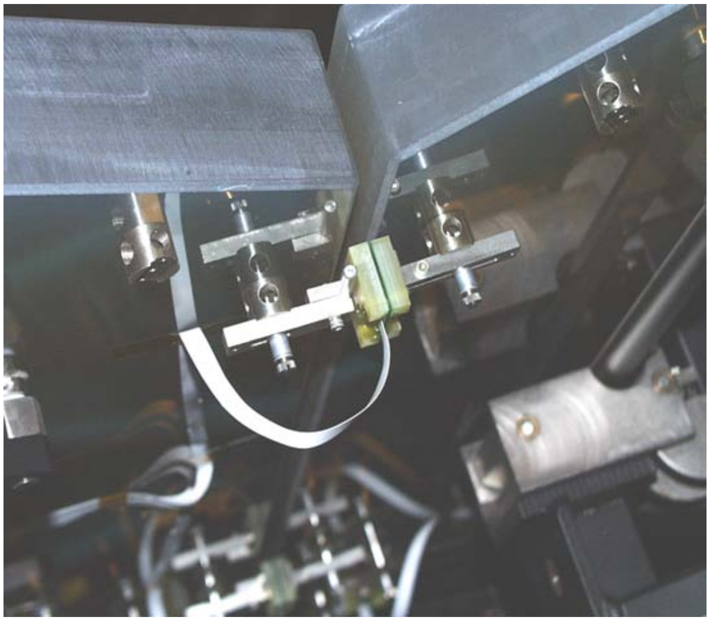

Figure 10: SAMS inductive edge sensors shown attached to rear surface of HET segments. Note second sensor pair near lower edge of photo.

SAMS is an edge sensor-based mirror control system similar to that of the Keck telescopes[21,22] in overall architecture, though SAMS uses inductive rather than capacitive sensors. Each edge sensor pair consists of an active coil and a passive coil (see Figure 10) that sense differential shear motion between segments. Individual segment tip, tilt, and piston errors are computed, and this error information is sent to the HET PMC. Positions are corrected every 90 s, although plans are in place to reduce this to 20 s in Phase II of the Completion Project.

SAMS has revolutionized the way HET is operated. Before SAMS became operational, primary mirror alignment was typically required once per hour and consumed 25 - 30% of the available nighttime operations hours. Since SAMS became operational, the median time between stacks has increased to 3.6 hours, with a corresponding decrease in the fraction of nighttime operations devoted to primary mirror alignment and an increase in the time available for science. The primary mirror array is now typically re-stacked only twice per night, with the first stack being performed at twilight.

SAMS is not yet fully operational over typical HET nighttime temperature ranges. The telescope has been observed to slowly lose segment tip/tilt alignment with ambient temperature changes beyond approximately 1 degree C of the temperature at which the segments were stacked. The destack rate increases with increasing temperature gradients. Sensitivity to temperature, and incomplete calibration of the sensors are thought to be the causes of this drift[23]. The contractor continues attempts to resolve this issue, and an in-house effort to analyze and solve this problem has been initiated as well.

A separate issue, maintenance of the Global Radius of Curvature (GRoC) or overall radius of curvature of the mirror array, has been problematic for SAMS[24]. GRoC is an unsensed mode for SAMS, whose edge sensor gaps all lie midway between segment edges. The original design concept to handle GRoC was the use of precision tiltmeters around the mirror array to measure dihedral angle change between segments. Temperature sensitivity of the tiltmeter electronics and other problems drove the design to the solution referenced above.

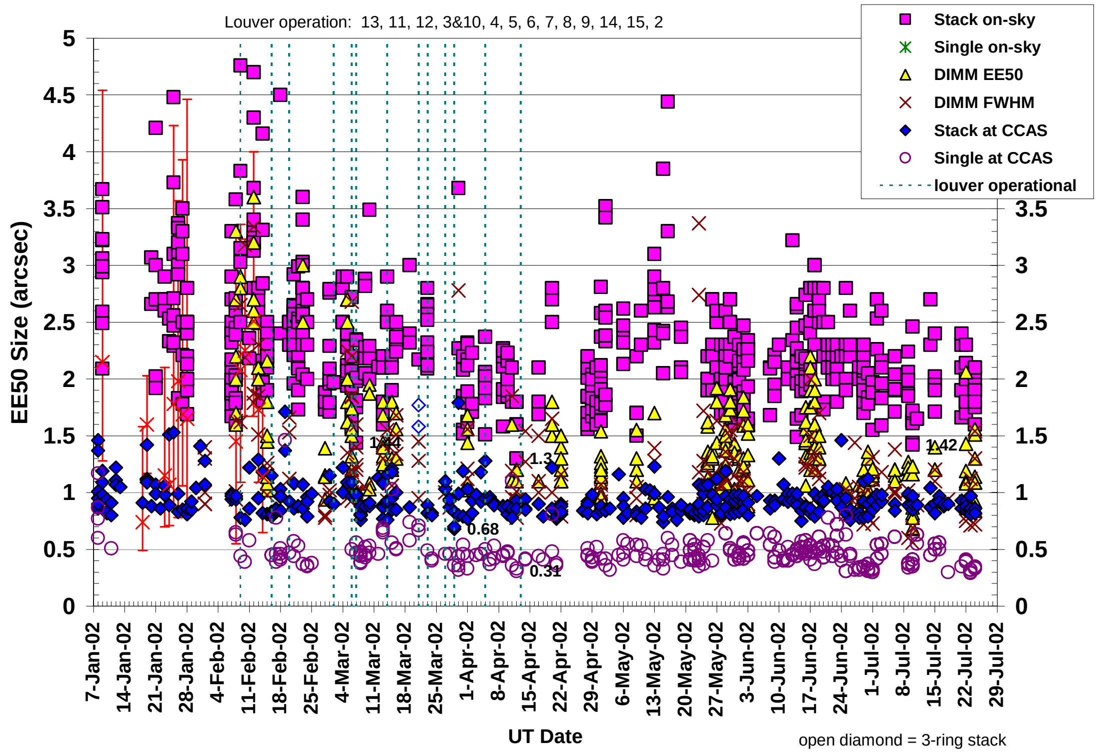

Figure 11: HET stacking and image quality history for Jan-Jul 2002. All values are EE50 sizes except as otherwise noted. Filled diamonds are stack size at the CCAS tower, open circles are single mirror segment size at the CCAS tower, filled squares are on-sky pre-science exposure image size, X's are DIMM FWHM, triangles are DIMM numbers converted to EE50 by a factor of 1.2. Dotted vertical lines indicate when individual louvers were installed for dome ventilation. The error bars on some DIMM points denote the max and min for that night with the median for the night marked by the X. DIMM points without error bars are instantaneous readings throughout a night The 2 open diamonds were 3-ring burst stacks and fall well above the MARS stack values. (From Wolf et al., these proceedings)

3.6. Phase I performance improvement summary

The chart in Figure 11 summarizes HET imaging and segment alignment performance since the first of this year (2002). The vertical dashed lines from February to April indicate the period of time over which the ring wall louvers became operational. Stack sizes at what is still referred to as "CCAS" are now generally below 1 arcsec, averaging 0.9 arcsec EE50%. We believe this is due to better segment alignment by the MARS instrument and better dome seeing.

More improvement is evident at the upper end of the image quality range (above 2.5 arcsec EE50%) than at the lower end. As we still have significant heat sources in the telescope dome, this is perhaps not surprising, as the new louvers allow much better flushing of the volume immediately around the telescope.

There are now occasional dips in image size below 1.6 arcsec (about 1.3 arcsec FWHM), typically under conditions of good dome flushing (winds 15-18 mph). Once the payload heat extraction system becomes operational in September

2002 and other elements of the Completion Project are finished, we anticipate a further improvement in dome seeing and on-sky image quality. With the suspected 1 arcsec problem within the SAC, sub-arcsecond image sizes will probably only be achieved once this problem is eliminated.

3.7. DIMM Project

Nightly operation of the two DIMM telescopes has produced the first long-term, consistent, and quantitative measure of the site seeing at McDonald Observatory[25]. A summary plot from the referenced work is included below for the first 13 months of operation. A clear seasonal dependence is evident, with the median seeing during the warmer months being about 0.3 arcsec FWHM better than in the winter (0.93 arcsec median of nightly means vs. 1.24 arcsec).

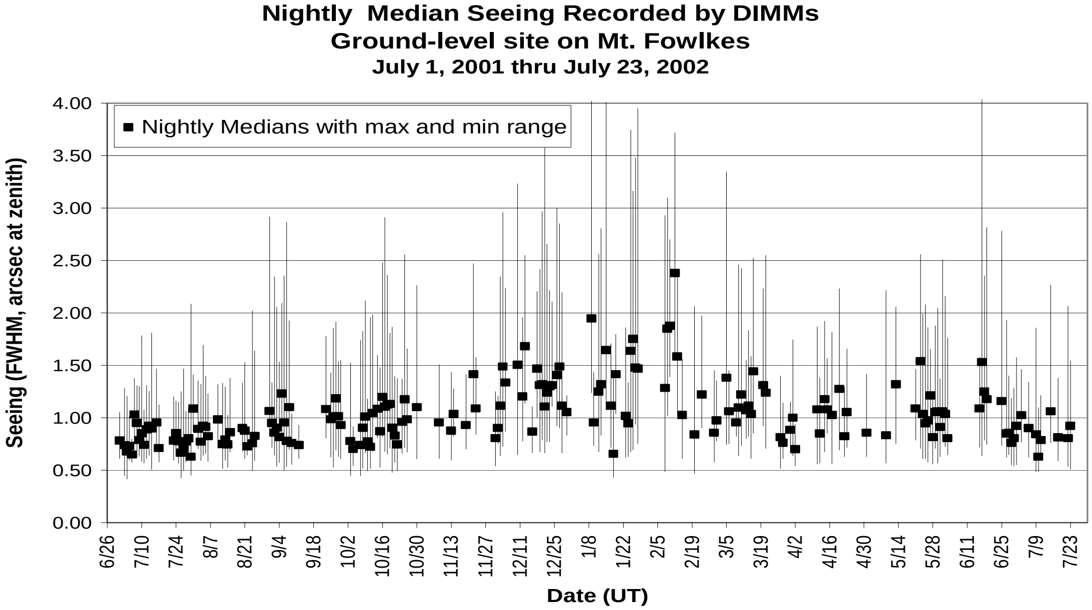

Figure 12: Median Seeing at HET (from Barker et al.)

Figure 13: DIMM1 and DIMM2 near HET

The DIMM telescopes are shown in Figure 13. They employ the now-standard technique first proposed by Roddier[26] and now in wide use among many large observatories[27,28] for measuring seeing using Kolmogorov theory and differential motion of two images of the same bright star.

Establishing a baseline site seeing characterization has been the primary goal of the DIMM effort, but the project has also provided HET with an important operational benefit every night the DIMMS are run (roughly 50% of the time). In the past, and especially prior to SAMS becoming operational in the fall 2001, the telescope operator and resident astronomer would determine when to re-align the primary mirror based on the on-sky image quality measured through the HET. (Now more direct stack quality information is also available from the SAMS system in the form of a “Global Error Variance” (GEV), which is the sum of the 480 edge sensor shear errors.) A poor image from HET was generally assumed to mean that it was time to restack the primary mirror. Once the DIMMS became operational, the night staff could separate “seeing bursts” from real segment misalignment, avoiding unnecessary stacking. DIMM operation also gives the night staff a means to discriminate between telescope defocus and periodic obscuration by clouds.

Plans are in place to construct a 6-m DIMM tower and dome southwest of HET, where one of the DIMMS will be operated in a remote mode from the HET control room. The tower height will allow sampling of the site seeing at a local elevation above the ground similar to that of the HET mirror. The tower and associated dome will also ease the nightly burden on the telescope operators of deploying and stowing the DIMMS manually, as is done currently. The new control system will allow much more automated operation, which will in turn increase the percentage of nights the DIMMs are operated.

3.8. Hartmann Testing

A Hartmann Test Fixture (HTF) was designed and built for making inside- and outside-of-focus images at the HET prime focus in rapid succession. Previous attempts at Hartmann testing involved either riding on the tracker (now not permitted for safety reasons) or long periods of time between the inside- and outside-of- focus exposures, during which the primary mirror alignment would change. This was because of the remoteness of HET prime focus from the ground, and the need to deploy the JLG lift for each camera movement.

The fixture is essentially a motorized PXL camera holder that can be driven along the optical axis of the telescope to the appropriate positions for Hartmann testing. Hartmann testing was performed in April 2002, for the first time with a relatively stable primary mirror (due to SAMS operation), and excellent mirror alignment (due to MARS operation). The new system is much superior to the old.

Results of Hartmann testing in April 2001 indicate potential for a residual 1 arcsec error in the HET optical train, after mirror segment misalignment is subtracted in quadrature from the raw Hartmann image. We suspect SAC mirror M5 is responsible for most of this error, as HET segments produce images that average much better than 1 arcsec, and the other three SAC mirrors were optically null tested during fabrication. At the time of M5’s manufacture (1996), a conventional optical null test had not been discovered.

Current plans are to change M5 out for a diamond-turned and possibly post-polished version of M5, while the original ULE M5 is analyzed and repaired. We are concurrently pursuing the development of a computer-generated holographic (CGH) null test for M5.

4. HET COMPLETION PROJECT, PHASE II

In Phase I of the Completion Project, we addressed dome seeing, initial segment alignment, segment alignment maintenance, and characterization of the HET site seeing. Each of these areas has produced improvements in telescope performance and our ability to operate the telescope more effectively. In Phase II, we plan to finish up remaining facets of these projects and move on to new image quality improvement areas. This section describes our plans for the Phase II effort.

4.1. Facility Thermal Management (FTM)

Understanding that everything affecting the thermal, and hence seeing, environment of the telescope needs to be systems-engineered, we have created a new project sub-area called Facility Thermal Management (FTM). The remaining dome ventilation and insulation tasks from DVS will fall under FTM, as well as the task of removing heat from the entire HET facility to a more remote location. The FTM top-level tasks are then:

- Ventilate dome structure
- Cover dome exterior with low emissivity film (e.g. WIYN, IRTF)
- Insulate dome structure
- Design remote EGW chiller facility to handle all in-dome nighttime heat source loads
- Convert from air extraction to EGW cooling of payload and electronics bay
- Remove heat-producing equipment near dome (e.g. large air compressors, transformers) to remote location

- Install remote facility Uninterruptible Power Supply (UPS) and remove individual UPSs.

4.2. Payload Re-engineering

The tracker payload is a densely packed volume with many critical HET subsystems. It consists of the SAC, the LRS, the Fiber Instrument Feed (FIF), which positions the input ends of the optical fibers feeding the HRS and soon-to-be-installed MRS, and acquisition and guiding systems. Most of these subsystems require upgrades, modifications, replacement, or repair. Additionally, we plan to develop at least one new subsystem, one that will close the position loop on telescope focus. As the telescope image quality has improved, defocus due to tracker mount model inaccuracies has become more noticeable. A summary of these Payload Re-engineering task follows:

- Develop closed-loop telescope focus control for tracker
- Characterize and fix suspected SAC M5 optical figure problem
- Environmentally seal payload and make light-tight
- Recoat SAC mirrors
- Upgrade acquisition and guiding systems for LRS, HRS
- Replace aging acquisition and guiding cameras with modern versions

4.3. Throughput improvements

Recoating the primary mirror and the four SAC with a more robust reflective coating have become priorities. When measured a year ago, the four protected silver SAC mirrors averaged 94% reflectivity in the visible. The primary mirror reflectivity has degraded considerably more since installation, and averages in the high 70%s. We plan to begin recoating primary mirror segments during Phase II, as well as the SAC, and are investigating the reportedly tough, broadband coatings under development at Laurence Livermore National Laboratory (LLNL) for this purpose.[29]

Throughput will also be increased by increasingly better image quality, and by fiber slicing at the HRS optical input. Implementing fiber slicing for the HRS is estimated to result in a factor of 4 improvement in throughput for this instrument.

4.4. Ops improvements (relating to telescope performance)

The Operations staff is involved in projects throughout the HET facility that improve the safety, operability, and maintainability of the telescope and its enclosure. Operations task that are expected to improve telescope performance specifically are listed below:

- Increase PMC segment position update rate from 90 s to 20 s cycle times
- Improve segment extraction/re-installation process
- Improve mirror segment cleaning, protection

4.5. Instrumentation

- Implement fiber slicing and other improvements on HRS
- Complete commissioning of HRS, LRS
- Install and commission MRS

5. PROJECT COST

The cost of the Completion Project over its projected 2.5-year life is approximately $2M. This includes all costs associated with design and construction of the DVS louvers, the MARS proof of concept and production instruments, and planned work over the next 12-18 months. SAMS was funded separately at about $1M.

It is worth noting the total cost of the HET projected to the end of 2003 will be about $24M. At that time, we expect that

HET will meet and in most cases exceed all of its original specifications. The costs break down as follows:

Initial construction cost, including use of accrued interest	$14M
Shakedown and commissioning	$2M
Instrumentation, consisting of the Low, Medium, and High Resolution Spectrographs	$5M
SAMS	$1M
Completion Project (DVS, MARS, many sub-projects)	$2M
Total	$24M

These amounts include all materials, labor, and consulting fees, and represent the real "out-of-pocket" cost of the HET through 2003, excluding operations costs. Telescope operation costs about $1.3M/year.

6. CONCLUSION

We have concluded a successful first year of the 2.5-year Completion Project The ring wall louver portion of DVS was designed, fabricated, installed, and brought into routine operation in less than 12 months. A new and much improved method for aligning the primary mirror segments (MARS) was conceived, designed, and implemented, with the design and construction of a follow-on final system well underway. The edge sensor system (SAMS) passed its Critical Design Review, was fabricated, installed on the telescope, and is in routine operation. Regular monitoring of the ambient site seeing is now performed and results are used nightly as part of the telescope operation. Telescope performance and efficiency has been significantly improved with the completion of these tasks.

Phase II of the Project will include completion of dome ventilation, insulation, and heat source suppression under the Facility Thermal Management subproject, completion of the final MARS alignment instrument, improvement of SAMS performance, closed-loop telescope focusing, SAC M5 figure characterization and probable figure mitigation, and recoating of the SAC. We also plan to begin recoating the primary mirror array during this period.

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