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Commissioning Experience with the 9.2-m Hobby-Eberly Telescope

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ABSTRACT

The HET is unique among 9-meter class telescopes in featuring an Arecibo-like design with a focal surface tracker. The focal surface tracker causes image quality and pointing/tracking performance to interact in a complex way that has no precedent in astronomical telescope system design and that has presented unusual demands upon commissioning. The fixed-elevation, segmented primary-mirror array offers some simplifications over traditional telescope design in principle, but has presented challenges in practice. The sky access characteristics of the HET also place unique demands on observational planning and discipline. The HET is distinguished by uniquely low construction and operating costs which affected commissioning. In this contribution, we describe those aspects of our commissioning experience that may impact how similar telescopes are designed, especially those with larger aperture, and review the challenges and lessons learned from commissioning a 9-meter class telescope with a small technical team.

Keywords: Hobby-Eberly Telescope, large telescopes, commissioning, segmented primary mirrors

1. INTRODUCTION

On 1 October 1999 the Hobby-Eberly Telescope (HET) ended commissioning and entered science operation. This paper describes some of the lessons that we learned in the commissioning process as they may apply to commissioning other large telescopes of this, or similar, design. The HET is further described by several other papers at this conference.

The HET was designed, was constructed and is operated on behalf of an international collaboration of universities: The University of Texas at Austin (UT Austin), the Pennsylvania State University (Penn State), Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. It is an Arecibo-like design with a focal surface tracker. The primary mirror is composed of 91 identical, 1-meter, hexagonal Zerodur™ segments arranged into a close-packed 10-meter by 11-meter hexagon. The primary is an unphased, spheroidal surface that requires correction by a Spherical Aberration Corrector (SAC) at the prime focus. The construction budget was limited to $13.5 million plus $0.4 million in interest funds. Key design elements of the HET are discussed in several S.P.I.E. publications[1,2,3,4,5].

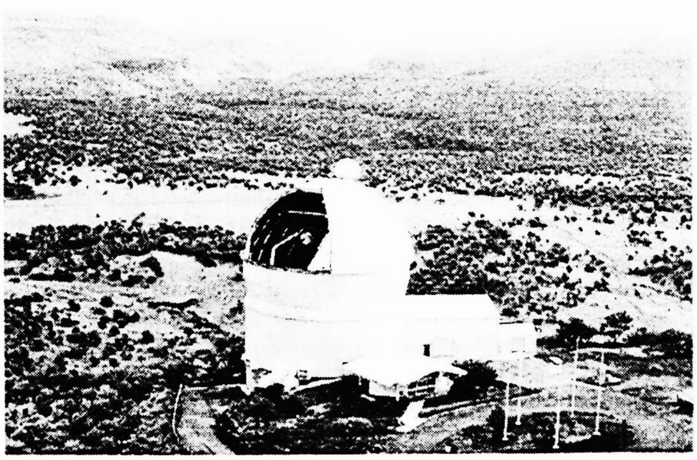

Figure 1 - A view of the Hobby-Eberly Telescope facility during commissioning. The payload on the prime focus tracker is visible as the white cylinder.

The concept for the HET is unique among optical, astronomical telescopes. There had already been major telescopes built with segmented primaries (MMT, Keck) and with alt-azimuth mounts (Russian 6-meter telescope, MMT, Keck) but no other major telescope had been designed with an Arecibo-style, prime focus tracker. More importantly, no 9-meter class telescope had been built for less than 6-10 times $13.5 million. To succeed would require both substantial innovation and substantial risk-taking on the part of the HET Project team. In many respects HET is a prototype, so there was a limited body of experience from previous telescope projects. Given the number of unique solutions that had to be created, the HET is a startling success.

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In designing and constructing the HET a number of decisions were taken that bear upon our commissioning experience. A brief outline of the HET Project in the five years prior to commissioning helps to put these in perspective. In Spring 1992 commitments to fund an innovative 9-meter class telescope had reached a level sufficient for UT Austin, acting as agent for the collaboration, to authorize hiring of a project team. T. A. Sebring joined as Project Manager in August 1992 and assembled a small technical team. This team expanded upon the concept originally proposed for the telescope; contacted potential vendors; and prepared the documentation for firm, fixed-price-bid competitions. A site was chosen on Mt. Fowlkes at McDonald Observatory in October 1993. Final legal agreements among the collaborators were signed in December 1993 stating a fixed cost of $13.5 million. Ground-breaking took place 25 March 1994. HET first light was achieved on the night of 10/11 December 1996. The Project team gradually departed during Spring 1997 as their duties were transferred to McDonald Observatory personnel.

The legal agreements among the collaborating institutions consisted of a bilateral agreement between UT Austin and Penn State, the founding partners, and additional bilateral agreements between UT Austin and Penn State, together on the one side, and each of the other three institutions, individually on the other side. With four legal agreements involving two public US institutions, one private US institution, and two public German institutions, the barrier to changing the legal agreements, once the project was underway, became substantial.

The decision to cap the cost of the telescope facility in the legal agreements had an impact upon subsequent developments. The first impact of this design-to-cost approach was upon the level of risk taken. The only hope of completing the telescope within budget was to use innovative design, which implied some risk of failure. The HET Project team had a remarkable record of successes. In this paper we are, however, concerned with those instances in which the facility did not achieve the performance desired, but these instances should not detract from the success of the Project team.

The second impact was upon the declaration of first light. By 1996 it was apparent that the HET would suffer a modest cost overrun. The legal agreements among the institutions had stated that those institutions contributing operating funds would commence payment upon declaration of first light. The very strong barrier to altering the legal agreements, the possibility of additional funds through the operating budget, and the unusual definition of first light for the HET all led to a strong effort to declare first light in Fall 1996. Upon successful first light 10/11 December 1996, operating funds became available retroactive to the start of the UT Austin fiscal year (1 September 1996), and the final months of the HET Project team were thereby funded.

The third impact was upon the public perception of completion of the HET. With first light in December 1996 the astronomical community would expect first science operations to begin in 1997-1998 rather than late in 1999 as actually occurred. The definition of first light for the HET required that only seven of 91 primary mirror segments be installed, aligned and form an image. (Seven segments made it the largest primary mirror at McDonald Observatory.) Compared to a classical telescope design, the HET was far removed from science operation when first light was achieved. Ninety-two percent of its primary mirror was yet to be installed and aligned (final segment installed May 1999); a surrogate spherical aberration corrector (SSAC) was in use (final SAC installed February 1999); and pointing and tracking were not reliable (reliable pointing and tracking achieved September 1997).

Lesson learned from this process: *an aggressive definition of first light carries with it the probability that the time from first light to science operations will be much longer than for traditional definitions.*

2. COMMISSIONING OVERVIEW

Planning for commissioning began in 1994 with creation of an Operations Planning team. Funds were made available by the HET Board of Directors to support a growing effort to define the operational budget, recruit the operations team, and transfer responsibility for the telescope from the HET Project team to HET Operations. This process led to approval of an extremely aggressive HET operating budget near $1 million per year and to a schedule for hiring the operations staff (12 full-time positions plus 3 level-of-effort positions from the McDonald Observatory staff). With departure of the HET Project team, the Operations Planning team was re-defined as the commissioning team in July 1997 with T. G. Barnes as Commissioning Manager.

In 1996 it became apparent that the HET construction project would have to end for fiscal reasons before the HET Operations team could be fully in place. The decision was taken to transfer responsibility for completion of the telescope through the permanent McDonald Observatory staff to the yet-to-be-hired HET Operations team. This double hand-off was only partially successful. The Project team was intensely involved with completion of the telescope and devoted little time to bringing the transition staff to full knowledge. They were also somewhat, and understandably, distracted by their search for new employment. In addition, the McDonald transition staff had incomplete coverage of the technical areas needed to attend to all the sub-systems in the HET. This transition process slowed completion of the HET significantly, certainly by many months.

Lesson learned: *it is advisable for project management to plan keeping the core of the Project team on the job through commissioning of the telescope.*

By September 1997 the major technical difficulties limiting pointing and tracking were identified and addressed. The first spectrum of a selected astronomical target was achieved on 5/6 September 1997 using ten installed and aligned mirror segments. With pointing, tracking and imaging capability, the HET officially entered commissioning on this date.

The HET facility was formally dedicated 7 October 1997. At that time the HET had 81 figured mirror segments and ten unfinished segments installed in the array but not yet optically aligned. The unfinished segments were returned to the contractors for optical figuring and coating after dedication.

In the first on-telescope test of the SAC and the Prime Focus Instrument Platform in August 1998, several design deficiencies were identified in the latter. These were corrected and the two assemblies were re-installed 19 February 1999. First science observing commenced 14/15 March 1999 using the Penn State commissioning spectrometer. The first facility instrument (the Low Resolution Spectrograph) began operation 14/15 April 1999. Full aperture was achieved in May 1999 with installation of the final mirror segments. The HET Board of Directors declared the end of commissioning and the start of science observations 1 October 1999.

3. PRIME FOCUS STAR TRACKER

The 12,000 pound, ten-axis, star tracker was delivered to the HET site on 25 September 1996 and assembled and tested in seven weeks in the basement spectrometer room. It was installed atop the telescope on 12 November 1996, and first light was achieved one month later. Converting this precise, gantry-type positioning device into an accurate, reliable, well aligned, robustly operating star tracking machine proved to be a much greater challenge for the Project team than had been anticipated. The tracker design is discussed elsewhere[6].

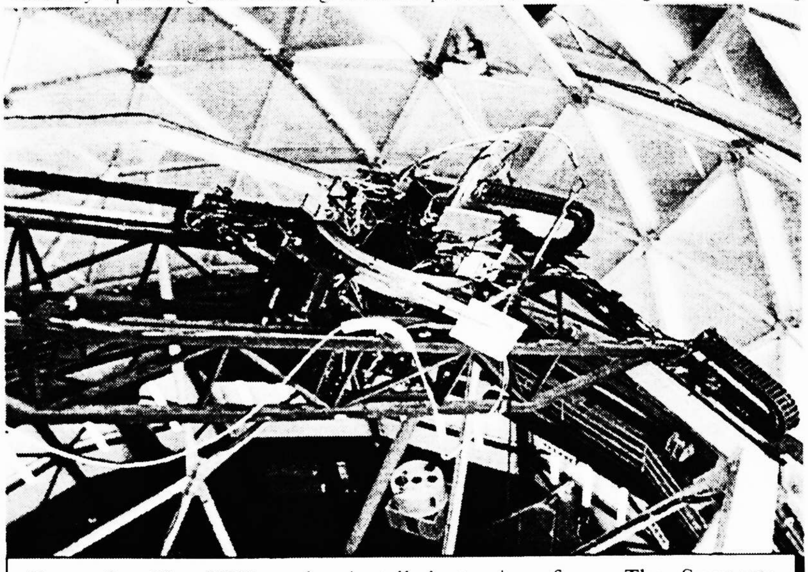

Figure 2 - The HET tracker installed at prime focus. The Surrogate Spherical Aberration Corrector, the white cylinder, may be seen on the dome floor.

A Prime Focus Instrument Platform rides on the tracker with the Spherical Aberration Corrector, Low Resolution Spectrometer, guiders and calibration systems nested within it. The four-element SAC contains reflecting surfaces of considerable manufacturing difficulty. Failure of the SAC to meet its construction schedule would bring the HET Project to a halt. Thus, an early and prescient decision of the HET Project was to purchase a simple Surrogate Spherical Aberration Corrector (SSAC) and to mount it at prime focus. This proved to be an outstandingly successful decision for commissioning. The SSAC optics are mutually-facing, concave, diamond-turned, aluminum disks forming a Gregorian re-imager. The f/1.8 output beam produced a flat focal surface over a 4 arcminute field of view. The SSAC was used for the first 2.5 years of tracker testing and debugging and proved to be enormously valuable to the commissioning process. The SSAC also permitted the process for aligning the primary mirror array to be developed and for initial science to be accomplished with the commissioning spectrometer.

Lesson learned: *If a back up system to a critical telescope component can be installed at modest cost, that cost is likely to be recovered through a more rapid commissioning time.*

There is no absolute frame of reference for the star tracker. Successful pointing of the HET required that a very large number of software parameters be adequately established simultaneously. Furthermore pointing and tracking in the HET are intertwined by the basic design. At the start of commissioning, pointing and tracking were insufficiently accurate to place targets stars within the field of view of the SSAC. The commissioning team overcame this situation by attaching a 100 mm f/5 telephoto lens to the SSAC module, yielding a relatively wide 15 x 20 arcminute field of view for early tracker testing. We installed a standard video rate camera on this lens which allowed us to see stars down to V = 5 magnitude. Co-aligned with the optical axis of the payload, the wide-field camera was essential for finding stars and determining the initial, large misalignments of tracker trajectories on the sky. When pointing better than a few arcminutes had been achieved, testing moved to the field of the SSAC. Eventually we could place targets reliably within 20-30 arcseconds of the SSAC field center. However, the imaging characteristics of the SSAC were not adequate to refine pointing beyond this and further improvement awaited SAC installation.

The four-mirror corrector (SAC) with its higher relative magnification proved to be much more sensitive to both misalignment and focus errors, as expected. A more accurate modeling effort was undertaken following final SAC installation 19 February 1999. Critical to HET performance is tip/tilt of the SAC relative to the focal surface of the primary mirror. A mis-adjustment here introduces substantial coma in the image. It soon became clear that attempts to align the SAC using stellar images would only be marginally successful due to a number of factors, including the changing shape of the pupil, weather, and difficulty in extracting useful diagnostic information from asymmetric images. A daytime method of alignment with greater sensitivity was required.

The method adopted was first suggested by Phillip MacQueen. A HeNe laser was installed in place of the acquisition camera within the PFIP and directed into the SAC *via* a 45° pellicle. The beam was aligned with the optical axis of the SAC using its central plug crosshairs. The acquisition camera itself was re-installed at straight prime focus; upon returning from the primary mirror array, the laser beam passed through the SAC, the pellicle and into the acquisition camera. Although the laser spot was relatively large, an accurate centroid of the spot could be obtained. This technique is differential only, measuring the changing angle of incidence of the laser beam on the primary mirror as the tracker moves the SAC within the prime focus field. An autocollimating alignment telescope was employed to accurately position the payload normal to the primary mirror array prior to beginning laser alignment tracks. In this way, payload variations from normal incidence could be detected as the tracker operated and removed in the software mount model. This is an excellent example of "fixing it in the software." Alignment of the SAC to better than 20 arcseconds, with respect to the primary mirror array, was achieved everywhere within the 3.8-meter tracker range of operation.

The HET tracker is operated from an adjacent control and service building. Early in the commissioning process there were several incidents which pointed to the need for better feedback to the operator regarding the status of the tracker. This led to the installation of a high fidelity audio system, a video system, and a Tracker Diagnostics System (TDS) during the commissioning process. HET's high-fidelity audio system allows the telescope operator to become familiar with the sounds of normal tracker operation. Telescope operators have, on occasion, reported subtle changes in the sound of the tracker, which were traced to significant mechanical problems, any of which may have led to substantial downtime. This system has proven so beneficial that it may be expanded to provide audio from other locations, such as the spectrograph rooms, shutter drive, and dome drive.

The HET uses video cameras in a similarly way. A camera can be targeted at a suspected problem area and provide immediate feedback to a distant location (including McDonald Observatory headquarters in Austin, Texas). Use is restricted to engineering operation because of the illumination requirements of the camera.

The HET Tracker Diagnostics System provides the telescope operator real-time information about the electromechanical status of the tracker. It displays commands issued to drive amplifiers, reports drive amplifier faults, limit switch status, and such. TDS: As installed the TDS provided incomplete and sometimes incorrect information about the state of the tracker. This led the operations team to design and build a replacement approximately two years later.

Lesson learned: *relatively inexpensive and well-conceived testing and diagnostic equipment, such as the wide-field camera, the audio and video systems and the TDS, can make the commissioning process more rapid and less difficult for the commissioning team.*

4. PRIMARY MIRROR ARRAY

The HET has a segmented primary mirror supported by a steel truss as an essential element of the telescope's low-cost design. During commissioning, the HET truss was gradually populated with 91 individual segments, and performance of the primary mirror array was improved to a level capable of supporting science operations. Key commissioning tasks included (a) the integration, verification and test of the hardware suite and software configuration that control the segments, (b) the development of algorithms that provide coarse alignment of the primary mirror array, and (c) the systems engineering that produced robust operations and acceptable on-sky image quality performance from the array.

Delivery of the last figured and coated segments from the contractors did not occur until August 1998, over a year after the Project Team had departed. Integration, verification and test of the primary mirror array hardware and software were therefore a commissioning task. Earlier delivery of the segments to the telescope site, preferably as soon as the dome was enclosed, and the structure complete and capable of motion, would have led to more rapid convergence of the primary mirror array performance. As noted previously, if the HET budget had been capable of supporting a 4 - 6 month overlap between the Operations Team and the Project Team, the primary mirror array commissioning time could have been shortened significantly.

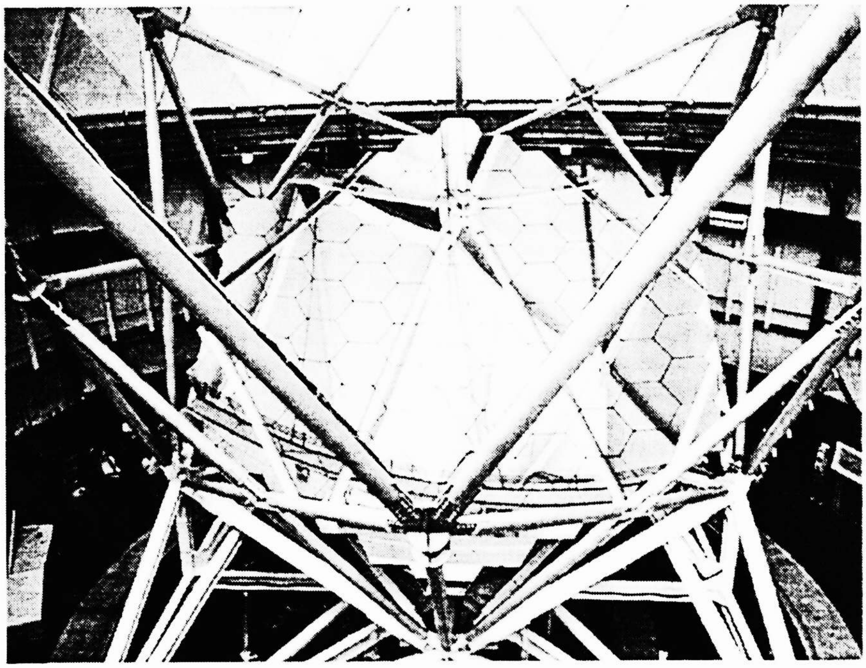

Figure 3 - A view of the primary mirror array of the Hobby-Eberly Telescope. There are 91 individual segments.

The only comparable astronomical telescopes with segmented primary mirrors are the MMT with 7 segments and the Keck telescopes with 36 segments. The Keck design called for edge sensors to keep the segments aligned under changing gravity and thermal loads. The HET fixed elevation design removed the need to compensate for changing gravity loads. It was hoped that inexpensive thermal sensors mounted on the primary mirror support truss and physical modeling would provide the required control over changing thermal loads. This choice was based on the assumption that the truss would act as an elastic solid body under temperature deformations. Much effort was expended early in commissioning to develop software techniques to align the primary mirror array in the presence of these temperature-driven deformations. This effort was not successful, and the failure is attributed to non-elastic motion of the mirror truss and to much more rapid thermal degradation than had been expected[7]. A consequence of this situation is that, under moderate thermal gradients that are within the performance specifications of the HET, the prime focus image degrades in quality on an unacceptably rapid timescale, leading to a limitation on the target integration time. Near the end of commissioning the HET Board of Directors contracted with Marshall Space Flight Center (Huntsville, Alabama, USA) and Blue Line Engineering (Colorado Springs, Colorado, USA) to develop and install an edge sensors system[8].

Lesson learned: *the steel truss design of the HET has thermal properties which limit performance of the telescope and which should be eliminated or worked around in future telescopes based upon this concept.*

To provide tip/tilt alignment and periodic assessment of segment piston, a Center of Curvature Alignment Sensor (CCAS) was purchased and delivered to HET. For tip/tilt alignment, the CCAS uses a dual-arm polarization shearing interferometer located at the center of curvature of the telescope primary mirror, 26.1 meters from the primary mirror array vertex. Light from a HeNe laser is projected to the HET primary mirror from CCAS, where it is reflected back to a focus at the entrance faceplate of the CCAS. The HeNe light passes through a pinhole in the center of the faceplate and enters the interferometer. It is collimated and split into two separate beams, each of these arms enters a pair of Wollaston prisms, which accomplish the image shearing[9].

Unfortunately, the CCAS hardware and software were delivered to the West Texas site long before any significant number of segments had arrived. Only cursory on-site testing of the device was performed by the contractor. By the time the primary mirror array was populated sufficiently for meaningful engineering tests of the CCAS hardware and software, the contractor had gone out of business and key individuals were no longer available. Given this history, it is not surprising that the CCAS has proved difficult to bring into operation. At the end of commissioning the CCAS still had no role in HET primary mirror alignment other than its use as a laser projector to facilitate coarse alignment. Recent (August 1999 - mid-February 2000) extensive engineering testing of the tip/tilt alignment arm of the CCAS has proved the physical optics. We have begun an intensive effort to assess the long-term role of the CCAS. Completion of this effort requires integration, verification and test of the electronics and the 8,100+ lines of software that process the fringe data. We expect this to be completed by May 2000.

Without the ability to use CCAS for primary mirror alignment, an alternative method was needed to commission the primary mirror array. This was addressed in four parts. First, the 91 segments are aligned in piston relative to the central segment using a manual spherometer hand-held by a volunteer suspended over the primary mirror array. This process has succeeded in establishing relative piston to close to the specified 5000 nm, and it is stable for months. Next the CCAS laser is used to establish the tip/tilt errors for each segment. At the start of the tip/tilt process, there is an amorphous aggregate of poorly aligned laser images on the CCAS faceplate. The first task is to identify the location of each segment image with respect to a reference mirror image. The second task is to calculate the tips and tilts necessary to "stack" 90 segment images onto the reference image. The third task is to move each segment under actuator control to the desired tip/tilt.

A camera mounted at the CCAS faceplate permitted images of the return laser spots to be obtained. By forming patterns with the return laser spots we are able to identify individual segments unambiguously. We use what we call a "burst pattern" that consists of concentric rings with a gap in each ring at a known position angle. This allows an automatic algorithm to identify the coordinates of each laser spot based on the radius of the ring and the angular position within a ring (by referring to the ring gap).

At this point, one might think that it would be possible to simply command each mirror to move to the reference mirror. The segments of the primary mirror are each oriented by three actuators, for a total of 273 actuators. The actuators do not have active encoders. The position of an actuator is reported by the controller, which counts steps. The combination of mechanical hysteresis in the mirror mounts and/or actuators and the lack of closed loop control dictated a more elaborate approach to tip/tilt alignment.

The effects of hysteresis are partially overcome by moving every segment image in the burst pattern back toward the reference image but by twice the angular distance. This forms a second pattern that we call the 'anti-burst pattern.' The position of a given segment image in each pattern is thus roughly the same angular distance from the reference image but in opposite directions. For each segment one can calculate a line joining the two measured images. The mid-point of each line is taken to correspond to the starting location of the segment image. At this point a file of tips and tilts can be generated which will move the laser return image from each segment onto that of the reference segment. These tips and tilts are the sum of the large motion necessary to get each segment image back to its starting location, plus the small motion to move it from its starting location onto the reference segment image.

The generation of the tip-tilt file mentioned above depends upon a transformation from CCD X-Y space to tip-tilt space. This requires knowledge of four variables dependant on the viewing camera location. Plate scale is mainly a function of camera distance from the CCAS faceplate. Viewing angle has the effect of turning circles of spots into ellipses. The position angle of these ellipses and rotation of the two coordinate systems with respect to each other are mainly functions of the direction around the face plate from which the camera looks and rotation of the camera about an axis normal to its CCD. The code which measures the spot locations, also solves for these variables on the fly prior to transforming from CCD X-Y space to tip-tilt space.

Because the star tracker assembly blocks the laser beam to/from some of the segments, the stacking procedure must be done separately for each half the primary mirror with a tracker move in between. The stacking process thus takes 9-10 minutes from the initial burst pattern to the final stack of all 91 segments.

Rapid progress in improving primary mirror alignment was made by implementing the stacking process. Nonetheless, alignment improvement was not as great as expected. It was realized that the sequence of motions described above does not fully eliminate the hysteresis. There is residual hysteresis in the final move to the reference mirror. Fortunately this hysteresis is sufficiently stable in time that it is sufficient to measure it empirically monthly. That measurement process takes 4-5 hours for 91 segments.

To track long-term progress in the primary mirror tip and tilt alignment performance, a simple metric was constructed, as given by equation 4.1.

$$F = N(\text{number of segments}) / t(\text{alignment time})\, I(\text{image quality}) \quad (4.1)$$

F is the primary mirror tip and tilt performance figure-of-merit; *N* is the number of segments installed and 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 (50% encircled energy diameter, EE50, in arcseconds) of the HET segment stack at the faceplate. The figure-of-merit increases as more segments are installed, as the time required for primary mirror array alignment decreases, and as image quality improves.

The primary mirror figure of merit would achieve F = 2465 if the HET were operating entirely at specification. The fully populated array would have N = 91. The original HET operations concept called for re-aligning the primary mirror array no more than once per hour, with coarse and fine alignment procedures that used no more than 6 minutes (t = 6 / 91 minutes per segment). Specification requires that the primary mirror array deliver an image quality of EE50 = 0.56 arcseconds, within 0.50 arcminutes of field center and in the absence of seeing (I = 0.56 arcsecond). In May 1997, prior to the start of commissioning, the primary mirror figure of merit stood at F ~ 0.3 (N = 7 segments, 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). Figure 4 shows the improvement in the primary mirror figure of merit for this period.

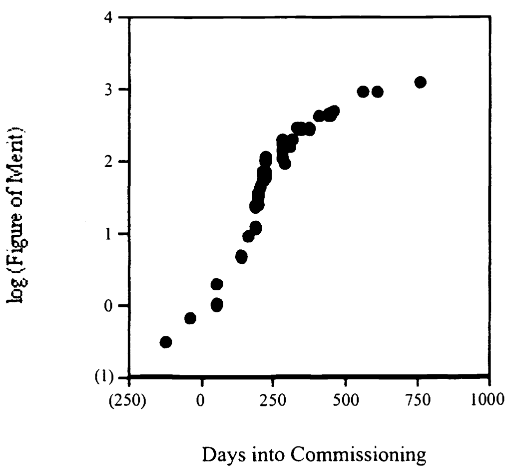

Figure 4 - Primary mirror performance Figure of Merit *versus* time

Three distinct improvement regimes are noted in Figure 4. For the first 10.5 months substantial performance gains were relatively easy to achieve. The number of installed segments increased from 7 to 41 and the functionality of the motion control hardware and software communications was integrated, verified and tested. Image quality performance improved by more than a factor of two. In the next five weeks substantial additional progress was made in improving the image quality and alignment speed. Much of this rapid improvement can be attributed to significant breakthroughs in the software that controls and manages communications with the individual segments and to the introduction of empirical corrections to compensate for hysteresis in the mount support hardware. The next year and a half saw the completion of segment installation, and a factor of five improvement in alignment speed owing to the cumulative effect of numerous small improvements. Particularly important was the incorporation of feedback from the telescope operators regarding how to improve the alignment procedures based on their commissioning experience. Image quality on the sky remained approximately constant, improving slightly.

By the end of HET commissioning, the individual segments of the HET primary mirror could be stacked to sub-arcsecond EE50 in 9-10 minutes, using substantially more robust software and hardware. The net gain in the primary mirror figure of merit was more than three orders of magnitude. 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 gave 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 nearly a factor of two above the requirement.

Few of the considered technical risks that the HET Project made have later been deemed problematic. The HET consortium has produced a viable 9-meter primary mirror array on a budget just 15 - 20% of comparably sized telescopes. Given the opportunity to build another HET-like segmented mirror array, of the same size or larger, we would obviously learn from this experience and do some things differently.

Lessons learned regarding the primary mirror alignment: *The CCAS sensor concept requires considerable re-design. A Shack-Hartmann sensor at either prime focus or the center of curvature is a viable alternative, though the roving HET pupil requires careful consideration and engineering design. Higher quality, higher cost mirror motion hardware would also have reduced the infant mortality problems experienced in commissioning the HET primary mirror array.*

5. THE HET FACILITY

The Hobby-Eberly Telescope facility comprises the enclosure, the adjacent control room, and their support utilities (HVAC, water, and sanitation). During commissioning we learned lessons worth communicating about the dome drive and HVAC systems.

The HET dome shutter is controlled by a PMAC controller. The controller sequences the release of shutter clamps, commands the shutter drive motor, and stops the motion once the shutter is fully open. It coordinates the reverse process to close the shutter. The PMAC controller, associated PMAC hardware, shutter drive amplifier, and various other electrical equipment are located in an electrical box on the rotating part of the dome within the enclosure. Although PMAC has proven to be an exceptional choice for motion control throughout HET, it is overkill for controlling a shutter. From our experience the shutter control system may be kept quite simple, without computer-based controllers. We plan to replace the controller with a classical electrical control system (relays, control switches, *etc.*), so as to improve the system robustness and reliability.

The HET dome drive consists of two identical drive assemblies located 180° apart. The drive motors are 7-1/2 horsepower (5.6 kilowatts) and manufactured for operation with a variable frequency drive. Figure 5 shows one of drive stations. The motors move the dome through a 39:1 triple-reduction helical gearbox by driving a rubber treaded drive wheel held against the steel dome drive ring by two coil springs. A continuous rubber seal seals the dome to the enclosure wall. The seal is about 6-inches wide by 3/8-inch thick.

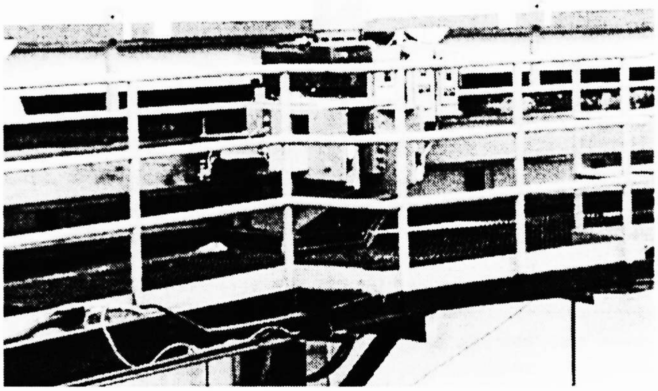

Figure 5 - A view of one of the two Hobby-Eberly Telescope dome drive stations.

Slipping drive wheels plagued early dome operation as did the dome drive tripping on following errors or over current trips on the variable frequency drives. It was recognized that frictional loads were contributing to the slipping drive wheels and over current trips. To reduce frictional loads, the continuous rubber seal was split vertically at dome section joints to reduce the friction generated by the seal. By splitting the seal vertically, the seal pressed against the stainless steel seal plate with less force, hence, less friction. The seal was lubricated with dry graphite, which also reduced friction. It was also noted that the dome skirt was rubbing on the struts that connect the dome enclosure wall to the Center of Curvature Alignment Tower. Efforts to eliminate the rubbing of the dome skirt were unsuccessful. The dome is supported on wheel assemblies called bogies. Investigation of the support bogies showed that they were not a significant source of friction in the dome drive.

Following the aforementioned actions to reduce frictional loads, efforts were concentrated on optimizing the drive train. The slipping drive wheel issue was resolved by the above actions and by adjusting the springs that hold the drive wheel against the dome drive ring to the maximum permitted compression according to the manufacturer's literature. The service life of the springs is reduced by this action; however, spare springs are maintained on site.

With the slipping problem corrected, the issues of the dome drive trips were addressed. The problems with the dome drive tripping on over current required analysis. The dome assembly weighs about 119,000 pounds (54,000 kilograms). Analysis showed that inertial and frictional loads were within the capability of the two dome drive motors; however, at the reduction ratio of the installed gearboxes, the motors operated on the low end of their torque curves. The motors were operating at less than half of their maximum frequency of 60 hertz. The 39:1 gearboxes were replaced with 114:1 gearboxes. The dome drive motors now operate on a more favorable portion of their torque curves with the replacement gearboxes while still rotating the dome fast enough to satisfy operational requirements. Presently, control of the dome motion and position are excellent. Because the dome supports the overhead crane, accurate positioning of the dome, and hence the crane, for mirror handling or installing equipment at prime focus is essential. With the dome drive modifications discussed above, the dome and crane can be positioned with sub-degree accuracy.

Fixing these dome drive issues created a new but minor problem. The dome drive presently experiences over voltage trips associated with generator action of the drive motors. When the dome drive control attempts to slow the dome, the inertia of the dome sometimes causes the motors to generate a voltage back to the dome drive that exceeds the over voltage trip point for the variable frequency drive. This condition can be fixed by installing what the drive manufacturer calls a regeneration resistor set. The first installed regeneration resistor set sized by the drive manufacturer proved to be too small. We intend to replace it with a larger one.

Lessons learned on the dome drive: *The dome drive should be designed and built so the dome drive motor operates on a favorable portion of the motor torque curve. While inertial loads can be precisely determined during design, conservative estimates must be given to frictional loads that can not be precisely calculated.*

As installed, the enclosure thermal conditioning equipment consisted of a single 50-ton (17.6 kilowatt) chiller and two 8250 cubic feet per minute (234 cubic meters per minute) air handlers. The air handlers are capable of operation from 100% re-circulation to 100% outside air. The air handlers are the draw-through type with a 5 horsepower (3.7 kilowatt) fan motor in the air stream. The return fans have the same capacity as the supply fans; however, the return fan motors are not in the air stream. The supply air ducts in the enclosure are mounted below the interior catwalk 30-feet (9-meters) off the enclosure floor. The top of the dome is over 40-feet (12-meters) above the catwalk. The chiller can provide chilled water at a temperature as low as 20°F (-7°C). The chilled water system has two chilled water pumps that circulate about 120 gallons per minute (454 liters per minute) of a 60/40 mix of ethylene glycol and water with a mixture freeze point of less than –20°F (-29°C). The chilled water system expansion tank has an 11-gallon (42-liter) draw down capacity. There are six downdraft fans with dampers installed in the enclosure wall that provide about 12 air changes per hour during nighttime operations. In the top of the dome are installed six dome vent dampers.

Originally the HVAC system was operated in 100% re-circulation mode, typical of commercial operations. As noted above, the supply air ducts are over 60-feet (18-meters) below the top of the dome. As a result, a hot air pocket develops in the top of the dome. Opening the dome vents is not effective in removing the hot air. By stopping the return fan, the dome is then positively pressurized, expelling the hot air pocket in about 26 minutes. The three dampers on the air handler for controlling the mode of operation are slaved together. One damper is master to the other two. This configuration limits the ability to control the dampers to achieve positive pressurization of the telescope enclosure; however, the configuration is suitable for commercial building applications. Another method to achieve positive pressure in the dome is to slow the return fan. Thus, excess supply air is discharged out the dome vents.

In addition, if the chiller tripped for any reason, the chilled water would continue to flow through the air handlers with the supply fans running. This causes the chilled water to heat up. As the temperature of the chilled water increased, the pressure would also increase causing the pressure relief to lift. This resulted in dilution of the glycol mix requiring the addition of glycol. As noted above, the installed expansion tank has a draw down capacity of 11-gallons (42-liter). The drawings required a 37-gallon (140-liter) draw down tank. The problem was corrected by installing a 42-gallon (159-liter) draw down expansion tank on the pump return line. Since the new expansion tank has been installed, no loss of glycol has occurred.

Operation has also shown that the chiller and air handlers are undersized. The peak heat gain of the telescope enclosure exceeds the ability of the system to cool the enclosure to nighttime opening temperature. This issue is dealt with by opening early and flushing the enclosure with the downdraft fans until primary mirror alignment can be performed. This adversely impacts telescope efficiency by delaying the beginning of nighttime science operations.

Foremost, the thermal conditioning equipment must be capable of providing positive pressurization of the telescope enclosure. Besides the issues discussed above, positive pressurization with filtered and conditioned air limits the infiltration of dust and dirt. It is much easier to change filters than clean mirrors. As discussed above, the dome seal is lubricated with graphite. Positive pressurization helps in keeping the graphite driven into the seal and away from optical surfaces.

Lessons learned from the HVAC system: *The most important lesson learned is that commercial HVAC configuration and methods of operation are not always suitable for telescope enclosure thermal conditioning applications. Control of individual dampers and fan speed is required to provide sufficient flexibility to achieve optimum thermal conditioning.*

The HET has greatly benefited from an emergency cutoff system (EMO). This system consists of large, red buttons located throughout the facility. In event of an emergency, such as a loud noise or unexpected/uncontrolled telescope motion, personnel can press any one of the buttons. This immediately shuts down the large moving mechanical systems, including the tracker, shutter, dome, and structure rotation. Several times during commissioning this system was used to prevent damage to personnel and property, especially during the early commissioning phases. The EMO system also has a lockout key provision. In the event that a particular subsystem is undergoing repair, one of eight lockout keys can be removed from the main EMO control box. This will inhibit motion of telescope systems until the repairs are complete and the key returned.

The HET control room contains approximately 10 computers, and associated hardware. Good practice dictates that all of this equipment be served by uninterruptable power system (UPS) power. During the commissioning of HET, a UPS was delivered for each of the computers as part of a particular subsystem. This resulted in a plethora of UPS within the control room. A much better design would power the control room from a single, or a small number of, industrial UPS.

The HET is served by an emergency power system installed during commissioning. This provides emergency power to close the shutter, preserve power to instrumentation and related CCD systems, preserve control room power, and provide auxiliary lighting in critical locations, such as the dome, electrical room, and the control room. The HET shutter drive system operates off of 480 VAC, while all of the other emergency system items operate from 120 VAC. The emergency power generator was installed to provide 480 VAC, with a medium-sized transformer providing step-down to 120 VAC. The system uses an automatic transfer switch (ATS) to sense a loss in facility power, start the generator, and switch to emergency power. This process is completely automatic. Installing the emergency power system post-construction led to several challenges, such as finding space for the transformer, ATS, and related electrical hardware.

It is common to use variable frequency drives (VFDs) in motor control applications in large telescopes. Designers should be aware that VFDs might induce unwanted electrical noise in unrelated systems. In the HET there are several sensitive electronic systems, such as precision temperature monitoring, that were adversely affected by VFDs. Our experience is that VFDs should only be used where absolutely necessary, and, if used, ensure that manufacturer recommended filters be installed to lessen the impact on other systems.

6. HET SOFTWARE LESSONS

The success or failure of any modern telescope depends critically on the reliability, flexibility, and extensibility of its software and computer systems. It is crucial to adequately budget time and manpower for software development. In the end, the HET Project budget covered only about one third of the software required for basic science operations, with the shortfall being made up during commissioning. Furthermore, much of the delivered software had to be rewritten, using more astronomically standard tools and software environments, to make initial science operations possible. Considerable time and effort could have been saved by adopting earlier available software from the astronomical community for standard tasks such as GUI building and image display.

The HET uses a heterogeneous, distributed computing environment to control the telescope and associated systems. The principal task of the observatory system in this type of environment is to distribute information between all the systems. The principal software task is communications. A robust communications and interface design, early in the software design effort, would have paid off in ease and simplicity of use later in the commissioning and operations phase. Unfortunately, the HET Project had insufficient software resources to put into communications, data format, and database standards early on, and communications between each pair of subsystems tended to be developed on an as-needed, ad hoc basis. Several communications channels were initially treated as "fire-and-forget", and it was only later realized that every single communications channel present would have to be two-way, with feedback on each command sent, to enable us to debug problems and guarantee performance later.

Early in software design a binary communications protocol was chosen. All data and commands are communicated as binary, floating point values. In practice this has lead to serious difficulty in troubleshooting communications problems as well as difficulty in porting software to different machine architectures. The binary protocol prevents the simple monitoring of communications channels and requires specialty software to debug communications problems. Such specialty software requires an additional phase of development, test and verification, and requires that a programmer be involved in every engineering debug task, when often a spreadsheet program and text-based data would have been adequate.

A binary, floating point communications protocol does not provide advantage over a printable ASCII protocol except in the case of large, numerical data sets. In the case of the HET, where command sets typically consist of fewer then ten commands, and the numerical data that are transmitted consists of a few to a few hundred three-digit numbers, a human readable communications protocol would have made software troubleshooting much easier. A simple, printable ASCII protocol allows the technician to bypass the majority of the software, to issue commands and monitor a communications channel quickly and easily. Indeed, a simple telnet interface to remote computer systems, with typed ASCII commands and plain text responses, would have provided a cheaper command interface than several Windows 95 based GUIs. The HET staff is in the process of converting binary channels to ASCII channels wherever possible. Only in the case of outside vendor systems where a binary protocol is already established is such a system required, and even then probably could have been avoided with better software specification up front.

During the commissioning phase an effort was started to upgrade the existing control system. The original control system could be used to test various aspects of the system but was very difficult to use for science operations. During this same period, a control system upgrade was in progress for the McDonald Observatory 2.7-m Harlan J. Smith telescope, and we combined both efforts in the hope that commonalties between the two control systems would allow a reduction in the total software effort. Certainly purely astronomical functions were more easily introduced into the HET control system in this way, by people with astronomical training. The resultant system, although very strong in communications, with a client/server architecture and a GUI kept separate from the underlying monitor program, does not have as much commonality as hoped. These two control system projects have now been split, and separate efforts are underway. This is imposed as much by organizational chart and funding arguments, as by differing software requirements. The low-level control functions that an operator sees of a classical, equatorial telescope and the HET telescope are quite different, but the interface to the astronomer can and should be similar.

The heterogeneous system design of the HET allows one to use the best hardware and software for each technical challenge. However, if care is not taken it can lead to a proliferation of hardware and software types, making troubleshooting and maintenance difficult for a small operations staff. Indeed, the initial architecture of the control system was specified by engineers with little software experience, and this process led to more computers than were necessary, and expensive local engineering interfaces to each subsystem, where a simpler, remote access, command line interface would have been cheaper, and easier to integrate into the final control system GUI. Early decisions in the design phase attempted to limit the computer systems to Sun workstations, for scientific data analysis, and to PCs running LynxOS, a real-time Unix system, for telescope and instrument control. Programmable Multi-Axis Controllers (PMAC), from Delta Tau Corporation, are used to handle most motion control areas.

Over time exceptions to this early decision have been made, though the earlier decision helped to limit the number of operating systems. Currently there are three versions of Sun Solaris (2.5.1 to 2.7), two version of LynxOS, DOS 6.2, Windows 3.11, Windows 95, and QNX (another real-time Unix system) used in the control systems of the observatory. The Windows systems have been particularly difficult to integrate with a centralized control computer. The programming staff is current working to consolidate and simplify this situation. For example, all of the software running on the Windows systems will be incorporated into other packages. Their current remaining function is to provide Ethernet to RS-232 translation and this can be easily handled with terminal servers. In practice it has also turned out that the real-time activities take place in the PMAC controllers and thus the real-time Unix system LynxOS is not required. The programs running under LynxOS will be ported to Solaris or Linux sometime in the future.

Since so much software had to be developed after the initial construction budget was exhausted, probably the greatest problem with regard to software was the lack of overlap between the construction staff and the operations staff. With the hard cap on the construction budget it was not possible to hire operations staff during construction, and it meant that the people hired to create the original control system were never meant to be long-term employees. It is an interesting psychological phenomenon that people write software differently if they know they will support it personally for a long time. This lack of overlap also meant that the operations/commissioning staff did not have a clear view of the decisions made during construction and spent 9-12 months just figuring out what the system was supposed to do, and how it did that. A special commissioning budget, that recognizes the need for this staff overlap, and provides funds to keep both staffs in place for 3-6 months, would have been helpful, as it would have been helpful to hire initially astronomical programmers for a longer-term relationship with the project.

Lessons learned: *hire a software engineer with real-world astronomical experience early in the construction project. A focus on communications robustness is crucial.*

7. SCIENCE OPERATION DURING COMMISSIONING

Part of the HET operations plan was to have 'science commissioning' observing during the commissioning phase. The primary purpose was to involve science users in providing feedback to the commissioning team and to help focus our very scarce resources on those efforts that had the highest impact on the ultimate science mission of the telescope. A secondary goal was to allow some early science dividend for HET researchers. The first goal was more successfully achieved than the second.

The Science Commissioning Team (SCT) consisted of a very few experienced observers from HET institutions. Seven scientists participated with a limited subset, highly active. Commissioning science runs were irregularly scheduled, typically following substantial change in an HET system. Only the fiber-coupled commissioning spectrograph provided by Penn State was available until the last six months of the commissioning period. This is not a facility class instrument and was not designed to do 9-meter class science. However, we did learn valuable lessons with it on acquiring, tracking and guiding on science targets as well as vital experience useful in the design of the fiber-coupled facility instruments for the HET. The SCT process also closely involved scientists in the telescope commissioning thereby welding a closer partnership with the evolving operations staff. Core team members used their experience to help define priorities for technical efforts that helped focus the commissioning effort. The most important result of the science commissioning effort relating to future operations was to give our communities and staff early experience in queue scheduling.

The science commission effort was not, start to end, a clear success. Like other aspects of the project it was resource starved which had the result that most team members could only devote partial energies to the endeavor. Similar future efforts should be structured to allow a small core team to devote nearly 100% effort for periods of months, not day or weeks.

On 14/15 April 1999 the Low Resolution Spectrometer (LRS) entered commissioning as the first facility instrument to be installed on the HET. It has been described in an earlier SPIE meeting[10]. The LRS achieved science capability very rapidly with the first publishable result obtained in the following week[11].

At the time of writing, the HET has been obtaining scientific observations with the LRS and UFOE for about five months. In this early operations phase, science is scheduled for two weeks per month, centered on new moon, with a week of instrument commissioning and a week of engineering. We expect this mode of operations to continue through the end of 2000.

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