Early performance and present status of the Hobby-Eberly Telescope

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

The early performance and present status of the Hobby-Eberly telescope

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ABSTRACT

The Hobby-Eberly telescope (HET) is a recently completed 9-meter telescope designed to specialize in spectroscopy. It saw first light in December 1996 and during July 1997, it underwent its first end-to end testing acquiring its first spectra of target objects. We review the basic design of the HET. In addition we summarize the performance of the telescope used with a commissioning spherical aberration corrector and spectrograph, the status of science operations and plans for the implementation of the final spherical aberration corrector & facility class instruments.

1. INTRODUCTION

The Hobby-Eberly telescope (HET) is an international collaboration and involves The Pennsylvania State University, The University of Texas at Austin and Stanford University in the United States, and Ludwig-Maxmilians Universität München, and Georg-August-Universität Göttingen in Germany. It is located at the University of Texas' McDonald Observatory near Ft. Davis Texas at an altitude of 2000 meters. This southwestern site is exceptional among US mainland developed sites for it dark sky.

The Hobby-Eberly telescope represents a unique and fundamentally different approach to building large optical telescopes. The HET design has been recently presented previously by Ramsey et al.[1] and Sebring, et al.[2, 3] and several key subsystems are described in detail by other papers at this conference[5,6].

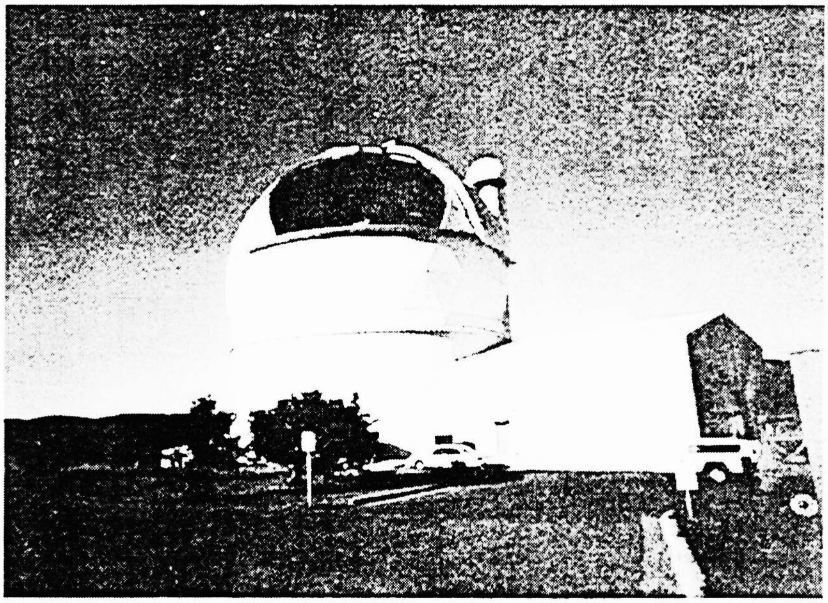

Figure 1. The Hobby-Eberly telescope facility

The Hobby-Eberly telescope had first light on December 11, 1996 and currently in the commissioning phase. We anticipated limited science operations to begin in early fall 1998.

2. TOP LEVEL SCIENCE DRIVERS

The HET concept results directly from the fact that a large collecting area will produce a spectrum or image of a given astronomical source rapidly thus enabling many objects to be observed in a short period of time. This facilitates surveys which are fundamental to understanding how the universe and its components work. Spectra are the major tool in probing the physical conditions of remote astronomical objects and the only way to probe their kinematic properties. The unique design of the HET derives from considering that telescopes are largely used for exposure times of an hour or less at modest zenith distances. In addition we have defined modest final image quality goals that are based on median site seeing rather than the best expected. This is consistent with a survey mission which cannot be driven by exceptional conditions.

The technical approach adopted in the HET design leads to a powerful yet limited telescope; a fact that is clear when one looks at the less than $15 million cost for this 9 meter class telescope. We have made considered trade-offs between cost and

Part of the SPIE Conference on Advanced Technology Optical/IR Telescopes VI • Kona, Hawaii • March 1998

SPIE Vol. 3352 • 0277-786X/98/$10.00

performance. While we expect the HET will fulfill a wide variety of scientific missions which were not at the heart of its genesis, it will be especially competitive when used with the following criteria in mind:

- Target classes are uniformly distributed on the sky
- Target objects have sky surface densities of a few per square degree or a few per square arc minute
- Time critical observations with time scales of days and longer are of interest
- Spectroscopy in the visible and near infrared yield the required astrophysics

Queue scheduling has been part of the HET concept since the beginning. This will allow the HET to be especially useful for investigators pursuing time domain astrophysics with the time scale limitations mentioned above. The HET will be especially competitive in planetary searches using radial velocity variations, monitoring of active galactic nuclei and quasar emission line strength and shape, and studies of activity and structure on stars and in accretion disks using Doppler imaging. For the latter program, the ability of the HET to acquire spectra rapidly with minimal phase smearing is essential. Survey programs such as optical identification of flux limited X-ray and EUV samples from space missions, investigations of the intergalactic medium by absorption of light in clouds on quasar lines of sight and precision abundance determinations in support of cosmology, stellar population studies and stellar evolution are also well suited to the HET.

3. HOBBY-EBERLY TELESCOPE FACILITY

Figure 2 illustrates the major features of the telescope and associated facility. As can be seen in Figure 2, the HET has a segmented primary mirror. The central (vertex) axis of this spherical primary mirror is tilted at a fixed angle making the HET a tilted optical Arecibo telescope with zero elevation freedom. However it has full azimuthal freedom allowing it to access different declination zones via this azimuth rotation. A motion of an object across the sky is followed by the *tracker* which carries the spherical aberration corrector and instrument package. This makes HET a nearly fixed zenith distance telescope within a declination zone delimited by the focal surface tracker field of view (FoV).

The telescope dome is a geodesic aluminum space frame structure about 86 ft. in diameter weighing about 30 tons. It is a modification of a structure that is more commonly applied as weather protection for oil and gas storage facilities. Its structural integrity is more than adequate for the survival wind and snow loads in west Texas.

The dome area where the telescope is located is thermally conditioned in the daytime by a chiller system. This holds the interior at temperatures near the expected nighttime conditions. When the dome shutter is opened for observing, six downdraft fans pull air through the opening at rates up to 20 dome volumes per hour. This system not only minimizes the effects of the facility on seeing but minimizes the temperature excursions of the primary mirror support truss.

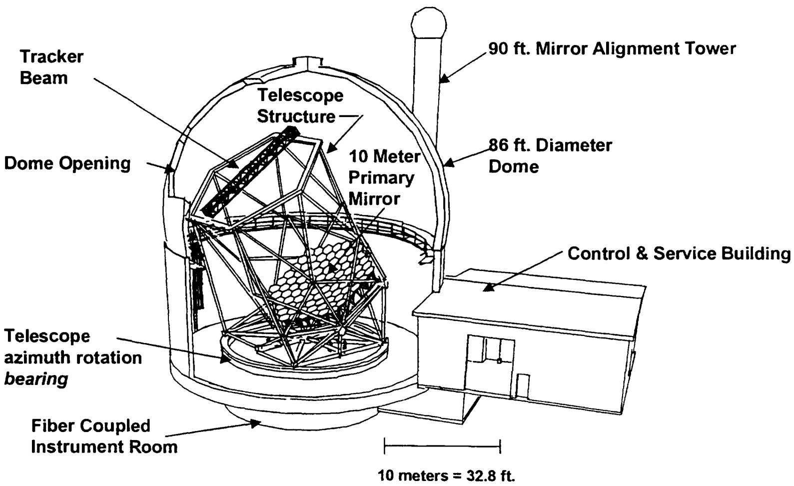

Figure 2. The HET Facility

The large instruments on the HET are fiber fed. They are located in a large instrument room under the telescope within the wall of the concrete pier that makes up the azimuth bearing. Optical fibers have a 32 meter path from the prime focus fiber instrument feed (Horner et al.[4]) though a hole in the pintle bearing. The cylindrical instrument room is on bedrock and its floor isolated from the rest of the HET facility so wind induced building vibrations are not transmitted to the instrument room. The wall of the instrument room is mostly underground and back-filled leading to an environment that is thermally stable on moderate time scales.

A visually striking element of the HET facility is the 90-foot tall tower to the north east of the telescope. This tower is constructed of two concentric welded steel pipe sections typically used for refinery towers. The inner pipe supports a platform for an alignment instrument located at the center of curvature of the spherical primary mirror. The outer steel tube supports the dome and provides an isolated wind shield for the inner tube.

A control and service building is located adjacent to the dome in the prevailing downwind direction. The control area, which is the only part of the facility routinely heated, is encapsulated inside this building.

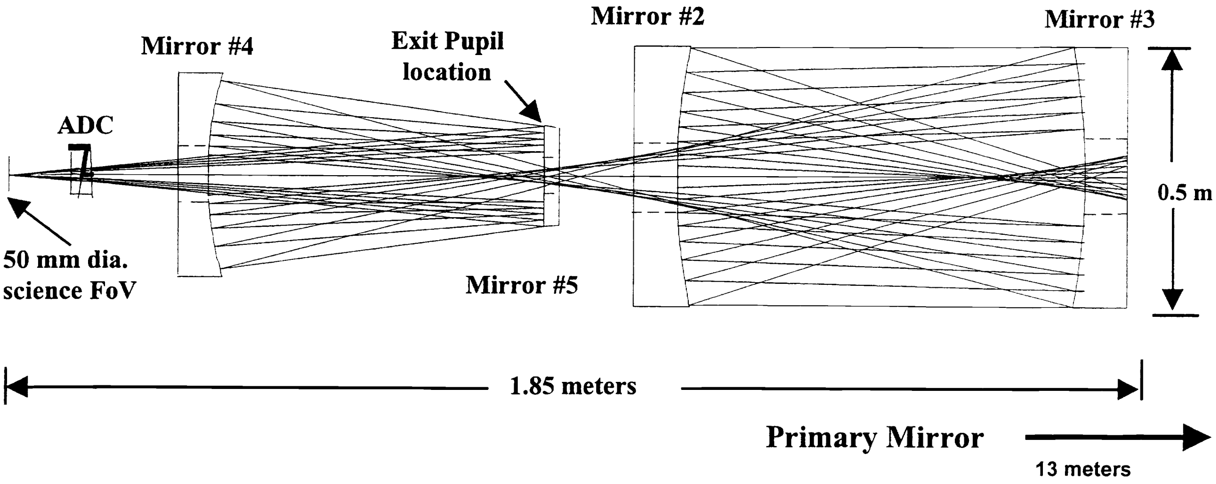

Figure 3. The HET spherical aberration corrector (SAC)

3.1 Optical System

The HET primary mirror is spherical and has a radius of curvature of 26.165 meters. An all reflecting four element spherical aberration corrector (Figure 3) removes the formidable amount of spherical aberration present at the prime focus of the primary and delivers a well corrected image over a field of view four arc-minutes in diameter. The corrector must move across the focal surface, which is a spherical surface 13.08 meters from the primary mirror center of curvature (CoC), all the time keeping its optical axis aligned with the CoC. This is done by the tracker whose capabilities are outline below and discussed in depth by Booth et. al.[5].

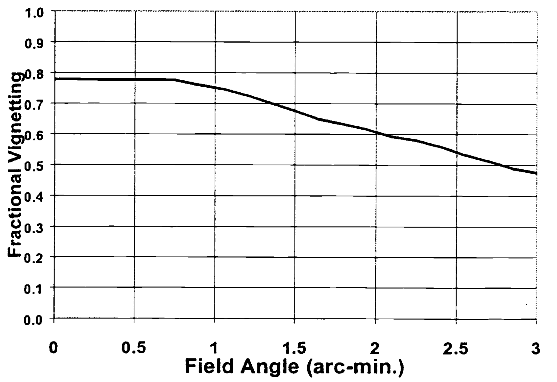

Figure 4. Fractional vignetting with field at prime focus

The HET spherical aberration corrector (SAC) is a 4-element design. Earlier, Ramsey et al [1], we were considering a two element corrector with a final f-number of 1.8. That was abandoned as it was a high order asphere and when it was combined with the optics required to feed most instruments, it proved to be complex and expensive. The adopted SAC is illustrated in Figure 3. Mirrors 2,3 and 4 are conics whereas mirror 5 is a low order asphere. All these mirrors are fabricated from ULE. The exit pupil of the system is near the surface of mirror #5 and projects to a 9.21 diameter entrance pupil on the primary mirror array. This is the maximum aperture of the HET.

An atmospheric dispersion corrector (ADC) is part of the HET design. Since the telescope is tilted at a fixed zenith distance and the excursion of the tracker is nominally +/- 6 degrees, a simple two-element ADC design is possible.

The science focal plane of the HET is 50 mm in diameter. With an image scale of 0.205 mm/arc-second, this yields a science field of view (FoV) of 4 arc-minutes. This focal surface is flat to about 10 μm to accommodate a focal plane low resolution multi-object spectrograph. The fastest f/ratio of the HET as built is f/4.68. The design of the SAC was severely constrained by the weight, space envelope available in the tracker as well as cost. This resulted in a trade between peak throughput and vignetting. Figure 4 illustrates the geometrical throughput of the HET as a function of field angle. As we move off axis the vignetting increases. The dominant issue in this regard is the size the of the central hole in mirror # 4. By making that hole large we can flatten the field response but at the cost of average throughput. In Figure 4 we extend the vignetting plot beyond the 2-arc-minutre science filed radius out to three arc-minutes. This is because the HET guide system is designed to operated out to 3 arc-minutes.

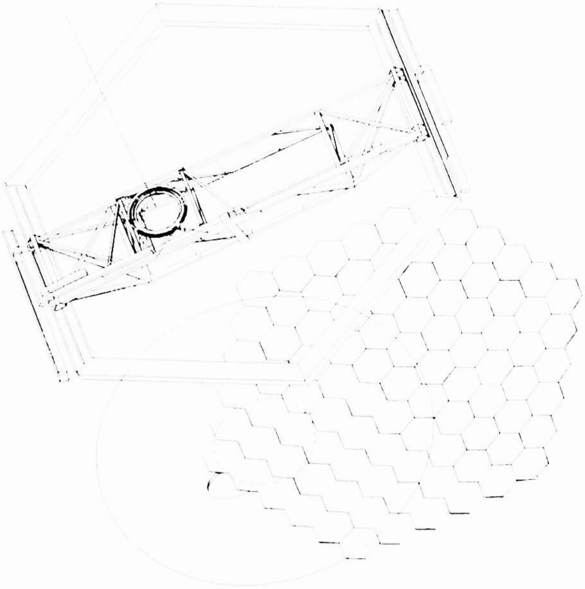
Figure 5. HET pupil off primary mirror array

An important effect that must be considered in the HET is a changing pupil illumination as an object is tracked across the sky. The corrector defines a 9.2-meter diameter pupil size, and it can "see" off the primary mirror when the tracker moves significantly off center. This is illustrated in Figure 5 where the projection of the exit pupil on the primary mirror is shown at a near extreme tracker position. The vignetting resulting when the tracker is significantly off center makes the average aperture of the HET a function of tracking time. For example, the effective aperture remains about 9 meters for short 10 minute tracks near the center of the tracker field, but diminishes to about 7.2 meters in the worst case off axis 40 minute track. This aspect of the HET demands careful consideration of baffling.

3.2 Primary Mirror

The HET primary mirror is an array of 91 hexagonally shaped spherical unphased segments. Figure 2 also illustrates the primary mirror array geometry. The mirror substrates are of Schott Zerodur and all the segments were figured by Kodak in Rochester New York. Krabbendam et al.[6] describe the primary mirror system in detail. Each hexagonal segment is 1 meter from flat to flat and has an edge thickness of about 50 mm. There are several strategies for packing hexagonal segments on a spherical surface. One can use irregular hexagons with regular spacing as was done by Keck. We have opted to use identical hexagons with an irregular spacing varying from 6.2 to 15.8 mm. This has minimal scientific impact but significant cost advantages. The packing fraction loss due to gaps and bevels is 3.44%. The total reflecting area of the primary mirror is 77.6 m^2. Each segment is coated with Denton FS-99 protected silver

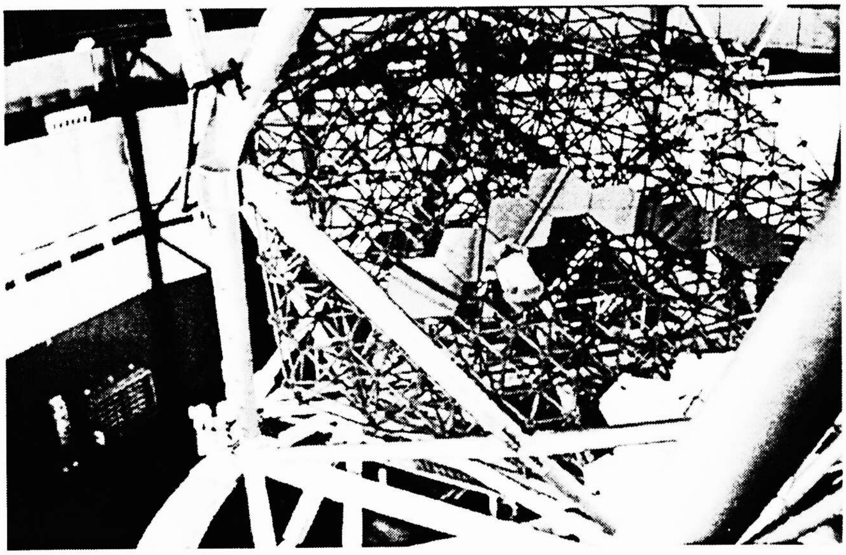
Figure 6. Mirror truss with 7 mirrors installed

The 91 mirror segments are supported on a metal space frame designed and built by Mero Stuctures in Wurzburg Germany. It utilizes a patented bolted assembly that has a stiffness equal to or exceeding a similar welded structure. It has a lowest resonant frequency > 10Hz when fully loaded. The truss has three nodes on the front surface for each of the 91 segment supports. These are reduced to three major mounting nodes on the back of the space frame where it interfaces with the telescope structure. This interface is through a kinematic mount utilizing linear bearings and special oil immersed ceramic pivots that keep the torque transmitted to the truss from the telescope structure less than 5 ft-lbs. Figure 6 shows the primary mirror as it was around first light with 7 segments installed. This picture illustrates nicely the mirrors and the metal mirror support truss.

An advantage of a spherical primary mirror is that a point at the CoC is re-imaged at that point. This provides a simple mechanism for alignment of the segments without having to acquire and track a star and to do so in the daytime if desired. However, this is not normally done as the best results are achieved if the mirror is aligned at a temperature very close to the nighttime use temperature. The system, called the CCAS instrument, for this alignment is a polarization shearing interferometer that allows for measurement of segment tip/tilt to 0.0655 arc-seconds. It is also specified to verify the segment piston tolerance of less than 25 μm.

3.3 Tracker

The HET tracker must provide for *all* tracking and pointing motions during observation. It was built by Orbital Sciences Corporation in Chandler Arizona and is described in detail by Booth et al.[5]. It is basically a 6-axis motion system which carries the corrector optics and the instrument packages. X and Y, up to 3.9 meters across the top of the telescope, are the primary motions to access positions on the mirror focal surface. A Z (focus) motion allows tracking on the spherical focal surface along with X & Y. Three other axes are required. Two angular axes, θ and φ, are required to keep the axis of the aberration corrector pointed at the CoC. A unique aspect of the HET tracker is that a hexapod system is used to implement the Z, θ and φ motions. A final axis, ρ, is a rotational axis to allow the focal plane to maintain a constant orientation on the sky. The tracker system as built weighs 4500 kg excluding the science payload and the prime focus instrument package. The tracker science payload includes the corrector, guider optics and the instrument package. An instrument payload capability of 200 kg is required with a goal of up to 400kg.

Figure 7. HET tracker

The size of the focal surface field of view is determined by the range over which the tracker moves. This square on the sky with 12° sides defines the tracker FoV. Figure 7 is a picture of the tracker and the top ring of the telescope structure.

3.4 Telescope structure

The telescope structure was initially designed by S, Medwadowski to provide maximum performance with minimum mass. The final design and construction was done by Comsat/Radiation Systems Inc. of Dallas Texas and has a lowest structural resonant frequency of 6.5 Hz and weighs 90 tons. The telescope structure has three fundamental functions. It provides support at the lower end for the mirror truss at an elevation angle of 55°. Secondly, at the top end, it provides a rigid support for the tracker. Lastly, it provides for azimuthal rotation. It is critical to realize that the HET structure has no elevation degree of freedom. It is fixed at an elevation angle of 55 ° (35 ° zenith angle). Observations to date indicate it is within 1 arc-minute of the 55° design angle (Glaspey et al.[7]). The final function of the structure is azimuth rotation. This is not a tracking motion but serves to access a region of the sky for acquisition and tracking. This is illustrated in Figure 8. Each square on the celestial sphere in Figure 8 shows the area of the sky that is accessible from one azimuth position. The azimuth positions are shown in 22.5° increments.

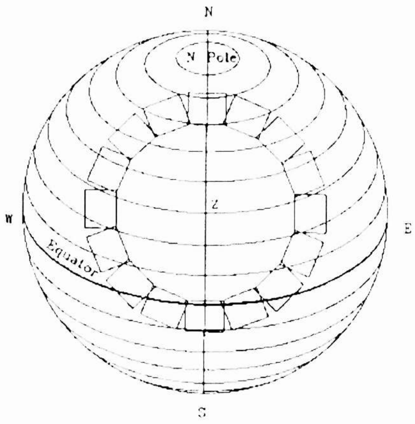

Figure 8. Tracker 12° FoV on the sky at different azimuth settings

The azimuth motion is accomplished with eight 36-inch diameter industrial air bearing on the smooth concrete surface of the telescope pier. The pier itself is flat to 0.01 inch. The air bearings proved a controlled lift of ~ 5mm at pressures on the order of 20 psi. The structure drive is provided by two rubber tires, each of which are directly driven by DC torque motors. These drives are separated by 180 degrees. The motion is extremely smooth. While the azimuth positioning itself need not be precise, it is critical that we know that position precisely once the telescope is positioned. This is accomplished with a precision encoder on the central azimuth pintle bearing.

At the latitude of McDonald Observatory (30° 40'), the primary vertex axis points at a declination $\delta = -4° 20'$ at an azimuth position of 180° (due South). As described above, when the HET rotates in azimuth, different declinations will be on the primary vertex axis. The HET has access to declinations from $-10° 20' < \delta < 71° 40'$ when the 6° tracker FoV is included. Sky coverage is limited to about 70% of what a general purpose telescope at the same site would normally achieve.

3.5 Prime Focus Instrument Platform

The Prime Focus Instrument platform (PFIP) is the heart of the telescope. This system contains the spherical aberration corrector and ADC as well as the acquisition camera system, the guide system and the exit pupil baffle system. It also has attached to it the prime focus low resolution spectrograph and the Fiber Instrument Feed (FIF). The FIF links both a medium and high resolution spectrograph to the telescope prime focus by way of over 150 optical fibers in a 32 meter cable down to the instrument room. Figure 9 shows a drawing of the PFIP with both the LRS and FIF attached. It is carried on the tracker hexapod which has a limited payload capacity as well as envelope within the tracker system. There is a high premium on light weight design for the PFIF and the instruments that are supported by it.

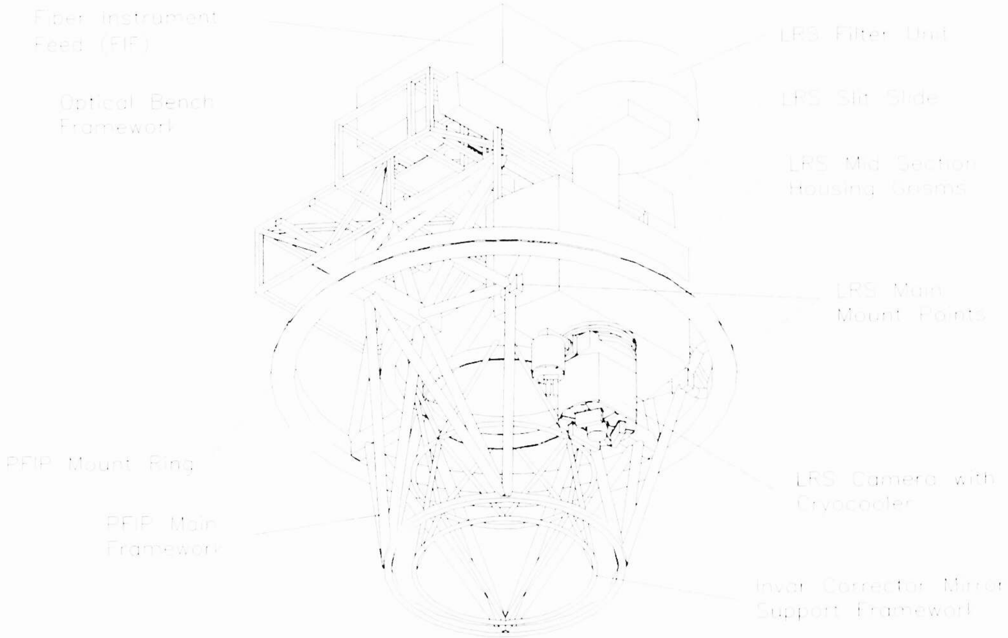

Figure 9. Prime Focus Instrument Platform

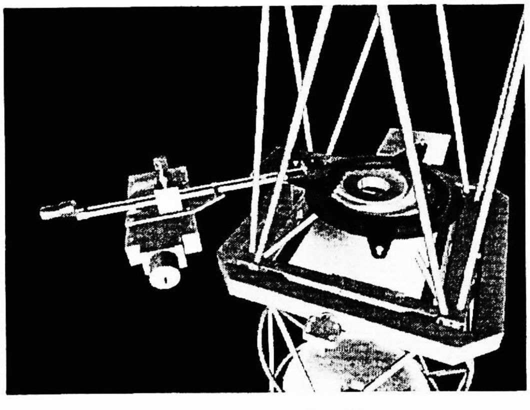

Figure 10. Exit pupil baffle system

As mentioned above, a critical function of the PFIP is to provide a pupil baffle for the telescope. When the telescope tracker is off center a significant fraction of the exit pupil which is formed directly in front of mirror # 5 is seeing light that can be scattered from the telescope structure and dome region off the primary mirror. This must be baffled. A moving pupil mask is placed directly in front of mirror #5 to accomplish this. This pupil baffle must translate in two orthogonal directions as well as rotate. The baffle mask is carefully cut to match the serrated pattern of the HET primary mirror array. Figure 10 illustrates this.

The PFIP system will be the final system to be installed in the telescope. With the delivery of the SAC mirrors in March 1998, the final assembley of this system can begin. The PFIP is scheduled to be integrated into the telescope in summer 1998. It will replace the test surrogate spherical aberration corrector system which is described in paragraph 4.1.

3.6 HET transmission

The transmission of the HET to the science focal plane is determined by three major factors. The first of these is the total geometrical obstruction. This is given as a function of field angle in Figure 4. It has a maximum value at the field center of 0.777 which includes losses due to the SAC central obstruction, bevels and gaps on the primary mirror and obstruction due to the tracker. The next factor is the atmosphere. The HET telecentric axis is tilted at 35° from the zenith. Thus the HET works at a nearly constant airmass of 1.22. The last major element is the reflectivity of the all the mirrors and transmission of the atmospheric dispersion corrector (ADC). The ADC is the only transmissive element in the HET. All the reflecting optics in the HET are coated with protected silver (Denton FS-99). We illustrate in Figure 11 the telescope transmission over its usable bandpass form about 350 to 1850 nm. The average atmospheric transmission at the 2 km altitude and total transmission to prime focus is given in Figure 12.

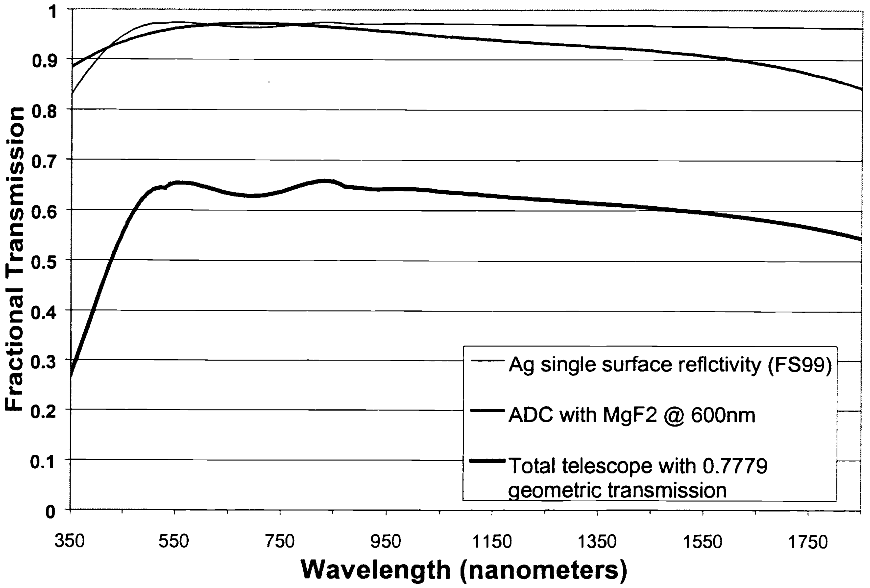

Figure 11. HET reflectivity and total transmission to prime focus

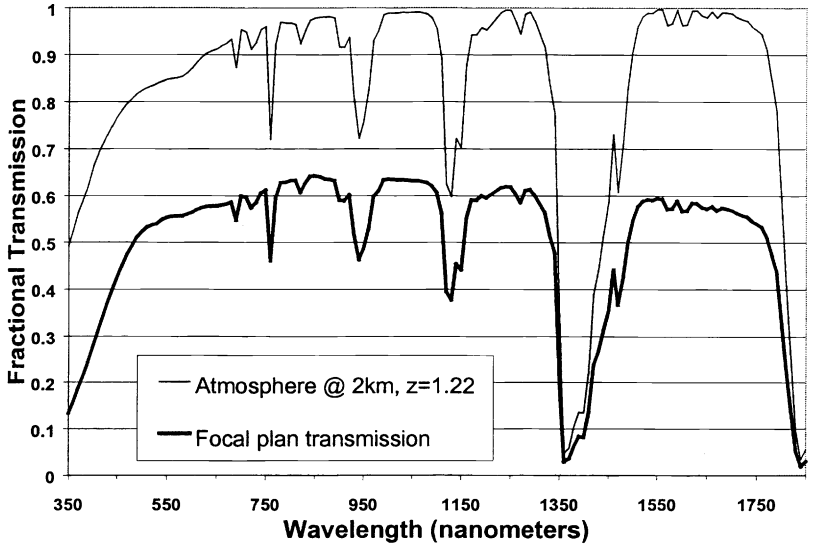

Figure 12: HET total transmission to prime focus with atmosphere

4. EARLY PERFORMANCE

4.1 SSAC

To facilitate early testing and accommodate a serious delay in the delivery of the SAC mirrors we fabricated a simple two element aluminum surrogate spherical aberration corrector (SSAC) using single point diamond turning technology. The SSAC was fabricated by II-VI Inc. in Saxonburg PA. The implementation of the SSAC was planned in early 1995 to facilitate early testing with a simple optic. This was fortunate as the last element of our final SAC was not delivered until March 1998; well over a year late. The SAC has been used in two different modes. The first mode is direct imaging mode where a Photometrics PXL camera is mounted directly at the prime focus of the SSAC. The second mode for the SSAC is with a unit called the SSAC fiber feed. This instrument uses the SSAC as the input to an optical system that simulates the guide and acquisition feature of the PFIP and feeds a test fiber to a commissioning spectrograph. Figure 13 is a schematic of this system. Here the output of the SSAC is collimated by a 50 mm f/1.4 Nikon SLR camera lens. In the collimated beam is a pellicle beam-splitter that passes 90% of the light and reflects 10% at 90o to another 50 mm f1.4 Nikon lens which forms an acquisition field on a SITe 1024^2 CCD in a PXL camera. The light that passes through the pellicle is then imaged by a simple achromat at f/4.6 onto a 2 arc-sec fiber that feeds the spectrograph. The fiber is in a hole in a reflecting decker that returns the light to the pellicle from the back side where 10% of that beam is folded at 90° to a third 50 mm f/1.2 lens which provides an image for a guide PXL CCD camera. This so-called SSAC fiber feed system has been used to test target acquisition, fiber centering and tracking tests as well as exercising queues for spectroscopic observations.

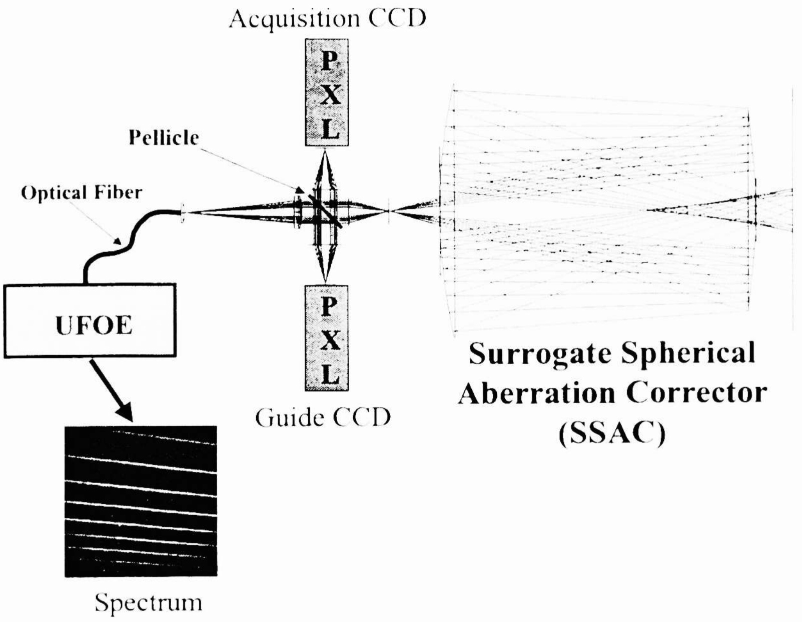

Figure 13: SSAC & SSAC fiber feed test configuration

The SSAC fiber feeds an simple optical bench commissioning spectrograph which we call the Upgraded Fiber Optics Echelle (UFOE). It is a 100 mm diameter beam grating cross dispersed echelle which uses a 400 mm diameter 4 meter radius spherical mirror to image the pupil on the echelle onto the entrance pupil a Nikon 200 mm f/2 camera. A 10242 SITe CCD in a Photometrics camera covers the 450 to 900 nm region with resolving powers from 3000 up to 13,000.

4.2 Pointing & Tracking

The largest success in the commissioning to date is the tracker subsystem. Pointing and tracking with the HET are intimately tied together and very complex. As an object moves across the sky the image of it formed by the primary mirror moves across a spherical focal surface in a great circle center on the primary mirror center of curvature. The focal surface which is totally synthesized in software only becomes reality when the tracker servo system executes precisely. Simplified, the tracker is a X-Y stage with a hexapod providing the needed addition degrees of freedom; eight in all. The tracking rates in these eight axes depend not only on the azimuth of the telescope but on the precise location of the target object on the focal surface. Furthermore the real focal surface location relative to the tracker depends on the exact orientation and location of the primary mirror array in the telescope structure. This can vary slightly due to thermal expansion of the telescope. Thus if the telescope is not pointing where the control software thinks it is the tracking rates will be off.

During the summer and early fall of 1997, we were able to achieve absolute HET pointing to better than 15 arc-seconds. Offset pointing should be considerably better but we have not yet exercised that fully. Tacking is currently 0.01 arc-sec per second or better. This does not yet meet the science requirements but we are confident that further mount modeling will improve this nearly an order of magnitude.

4.3 Primary Mirror Performance

The primary mirror has always represented the greatest technical risk area in the HET project. The baseline design has the 91 Zerodur segments sitting on a steel truss with no sensors tracking their relative positions. Since the gravity vector through the primary mirror is constant with respect to gravity the only effect on the mirror positions are thermal. The approach we have adopted is to allow 6 minute per hour to tune the primary mirror array using the CCAS instrument. Success in this requires that small piston adjustments be made over short time intervals to account for the global change in the truss shape as the temperature changes. This is done using a first order thermal model.

To date we have successfully stacked 40 mirrors to better than 1.5 arc-second at the CCAS instrument. The image quality on the sky is typically somewhat worse due partly to the limitations of the SSAC and partly to variation in truss temperature. The changes with time appear to be directly correlated with the truss temperature change as is expected. We are in the early stages of experimenting with the thermal algorithms and expect further improvement with time. Our goal is to achieve 1 arc-second images with at 80 or more mirrors by summer. After that we will refine the system toward our goal of 0.6 arc-seonds with the full compliment of 91 mirrors.

5. INSTRUMENTS

There are three facility instruments in construction for the HET. A low resolution multi-object imaging spectrograph ($600 < R=\lambda/\Delta\lambda < 3000$) covering the wavelength region form 350-1200 nm is described by Hill et al[8]. This is the only focal plane instrument. A fiber fed medium resolution ($3600 < R < 20000$) spectrograph with both multi-object and integrated field unit capabilities is described by Horner et al[4]. Finally a fiber coupled high resolution ($30000<R<120000$) spectrograph is described by Tull[9]. The low resoution spectrograph will be the first facility instrument and will be commissioned in summer 1998. This will be followed by the other instruments in the first half of 1999.

6. ACKNOWLEDGEMENTS

We would also like to thank Robert E. Eberly of Pennsylvania and Lt. Governor William P. Hobby of Texas and other contributors which have made the Hobby-Eberly Telescope possible. We also acknowledge the continuing contributions of the recent additions to the HET operations team; Craig Nance, Grant Hill, Matthew Shetrone, Francois Piche and Brain Roman.

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