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Hobby-Eberly primary mirror fabrication

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ABSTRACT

The 11-meter primary mirror of the Hobby-Eberly Telescope consists of 91 hexagonal segments. Each segment is 1 meter across (flat to flat). The unique design of this telescope allows for a spherical radius of curvature on each segment. Requirements are that each segment's radius of curvature match to within ± 0.5 mm of the nominal 26,165 mm radius, and that the surface figure be within 0.033 μm RMS. The optical fabrication, testing, and assembly of these segments will be discussed along with a description of the segment mounting scheme.

Keywords : optical fabrication and testing, telescope, primary mirror

1. TELESCOPE

The William P. Hobby - Robert E. Eberly Telescope (HET) is being built atop Mount Fowlkes at the McDonald Observatory in the Davis Mountains of west Texas. It is the first major telescope designed primarily for spectroscopy rather then multi-purpose visual sciences.[1] The telescope is being funded and built by a consortium of universities including: The University of Texas at Austin, Pennsylvania State University, Stanford University, The University of Munich and the University of Goettingen. Eastman Kodak Company (Rochester, NY) was chosen to fabricate 96 primary mirror segments for this project.

The focus on specific scientific missions allows for uniquely cost-effective approaches in the design and operation of the telescope.[2] A significant feature of the telescope is its fixed elevation pointing vector. The structure and primary mirror of the telescope remain fixed at an elevation of 55° from the horizon. The telescope is rotated in azimuth to access a region of the sky and a tracker subsystem located on the top of the telescope moves the secondary corrector assembly and instrumentation along the focal surface of the spherical primary mirror to track objects for observation. Throughout the year, 70% of the sky can be accessed and objects can be viewed for one to two hours at a time, depending on the specific trajectory across the ±8.5° tracking field. By moving only the optical package on the tracker, the large heavy parts of the telescope remain stationary and the primary mirror remains fixed with respect to gravity.

The 11-meter HET primary mirror is an array of 91 identical hexagonal mirror modules supported by a single 25,000 lb truss. Each mirror module weighs 315 lb and is optically and dimensionally identical for complete interchangeability. A module consists of a 250 lb spherically polished Zerodur™ optical segment, a nine-point segment support structure, a center lateral support, and a three-actuator position and control system. The entire primary mirror is mounted kinematically in the telescope structure causing dimensional variations in the telescope to result only in rigid-body motion of the primary mirror.

Position feedback for the primary mirror modules is performed with a 2-channel simultaneous acquisition phase shift lateral shear interferometer located at the center of curvature. This center of curvature alignment sensor acquires tip and tilt information to 0.005 arc seconds and piston information to 5 microns for each segment as a relative value against a reference mirror module.[3] Data is taken between observations when the telescope rotates to point at the center of curvature tower directly adjacent to the telescope building (Fig. 1). Operational plans allow six minutes per hour for primary mirror alignment operations.

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An 86 ft diameter 5/8 spherical dome will enclose the 90 ton telescope. The prefabricated aluminum geodesic dome weighs 50 tons and rotates to keep the single shuttered opening aligned with the telescope azimuth position. A down draft ventilation system maintains a uniform temperature throughout the telescope dome with six variable speed exhaust fans pulling air through the dome opening. A separate environmental system maintains the temperature within 0.2°F in the basement spectrometer room where fiber fed instrumentation is located.

The primary mission of the Hobby-Eberly Telescope is spectroscopy. Science will be performed from several instruments located both on the tracker using the output of the corrector and in the basement spectrometer room using fiber transported light. Spectroscopy reveals the temperature, chemical composition, and motions of astronomical objects. The large collecting aperture of the HET will allow astronomers to study much fainter objects and learn more about how the universe and its components work.

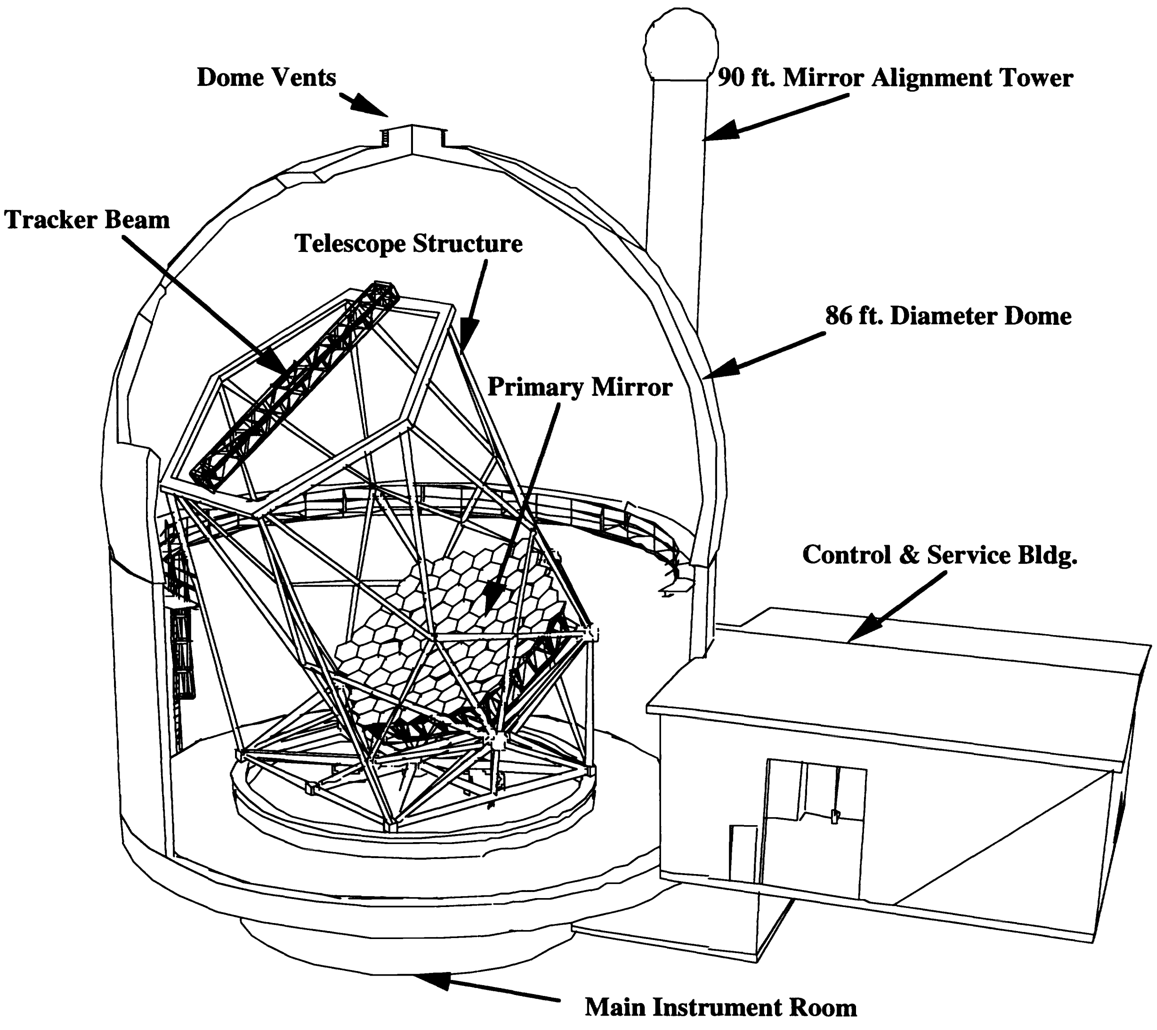

Figure 1. HET Telescope

2. PRIMARY MIRROR REQUIREMENTS

The HET primary mirror array has an area of 78.806 m^2. Each of the segments are spherical with approximately a 26 m radius of curvature. All segments are the same size (1 m flat to flat). Intersegment gaps are allowed to vary to accommodate a uniform segment size.[4] The gap sizes vary from 6.2 mm to 15.8 mm. The gap throughput loss is 2.04%. Because of the primary mirror fixed elevation design, the segment support concept is required to minimize segment deflection for the angular orientation differences found at the various positions in the array. This allows the fabrication of all segments to a mount at a nominal angle and the interchangeability of all supports and mirrors. The segment support consists of 9 axial supports and a center radial support. The center radial support interfaces with a blind hole in the back of the mirror. The 9 axial supports are divided into 3 groups each supported by a Invar tetrahedral frame. Nine Invar buttons are cemented onto the back of the mirror forming the contact points with the tetrahedral frames. The mirror buttons simply set on 9 ball pivots, which are attached to the 3 tetrahedral frames. The support also incorporates a lever system allowing 3 actuators to adjust tip/tilt and piston (one actuator per tetrahedral frame).

Deformation of the segments due to gravity occurs between the nine support points of the segment support mount. The resulting mount/gravity deformation must be compensated for during optical fabrication to maintain the required optical figure at the nominal elevation angle. The optical axis or axis of symmetry of the part must be inclined at 55° from horizontal during final optical testing. Table 1 summarizes the primary mirror requirements.

Table 1
Mirror Requirement Summary

SPECIFICATION	TOLERANCE
Radius of Curvature	target radius 26,165 mm ± 10 mm all segments to be within 0.5 mm of each other (0.192 λ PV)
Optical Figure Quality	0.033 μm RMS (0.052 λ RMS)
Scratch/Dig	60/40
Micro-roughness	20 Å RMS

3. PRIMARY MIRROR METROLOGY

Primary mirror metrology is based upon interferometrically measuring the segment's spherical surface against a full aperture convex test plate (Fizeau interferometer). In this test configuration the full aperture convex test plate is held in close proximity to the segment optical surface while the segment surface is held in its mount at the specified 55° elevation angle. The test plate is illuminated with a laser point source and the resulting interferogram is recorded from the position of the image of the center of curvature of the test plate reference surface as seen through the second surface of the test plate. This condition ensures that the illumination reaching the reference surface is approximately normal to that surface. The separation between the mirror surface and the test plate is approximately 6 mm (Fig. 2).

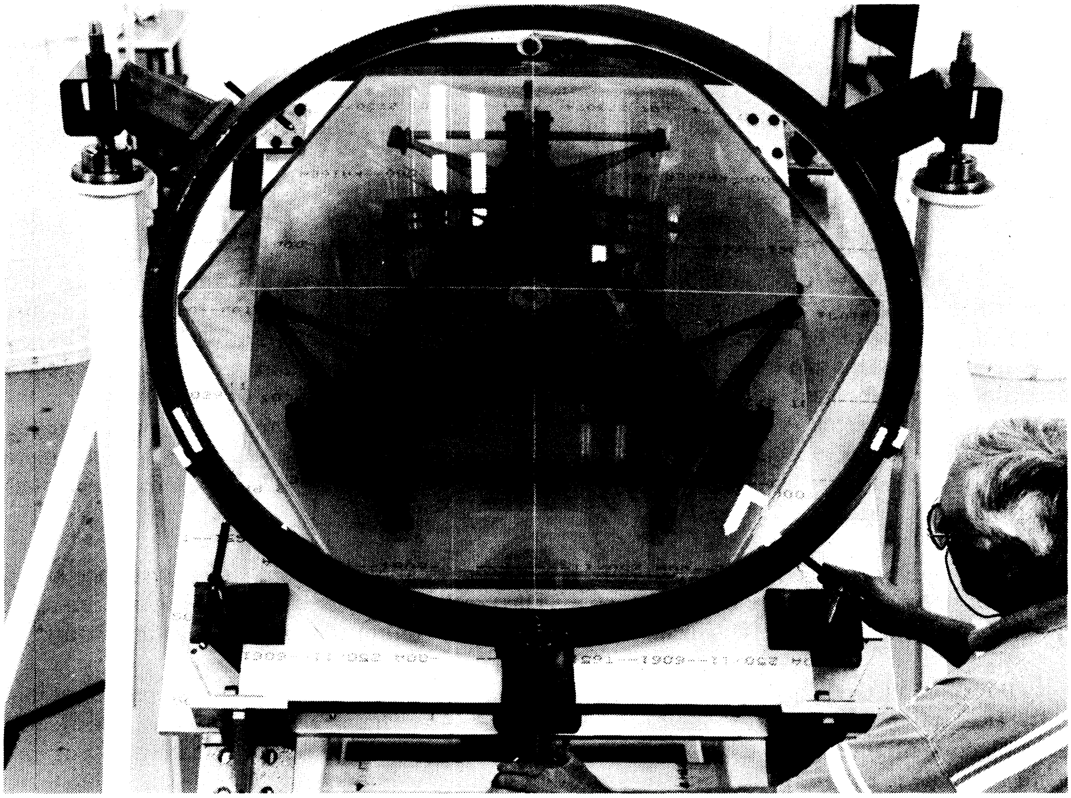

Figure 2. HET Mirror in Test Set

The convex test plate is calibrated against a concave master fabricated specifically for this calibration effort. The master is a ULE optic 1.3 m in diameter and 200 mm thick. The concave surface of this optic is spherical with a radius of curvature of 26,165 mm when held in its holding fixture at an elevation angle of 55°. The deflection was independently characterized such that the mounted master segment serves as a known reference to fabricate the full aperture test plate.

The test plate is a 1.1 m diameter, 127 mm thick fused silica test optic. The first surface has a convex radius of 26,159 mm. The second surface has a convex radius of 3 m to allow positioning of the laser/camera at approximately 3.6 m from the back surface. The final radius and figure of the first surface was made to match the surface of the master segment after the master segment had been characterized. Verification of the radius of curvature of the master test plate was done as follows: The radius master was tested interferometrically. This test was a conventional interferometric test performed at the center of radius of curvature of the radius master. The master's orientation was vertical for this test. Its radius of curvature was measured using Invar rods. The radius of curvature of the master test plate is 26,163.92 mm as reported on September 9, 1994. The master also had its surface deflection mapped at the 55° elevation angle.

After the radius of curvature of the master was verified to be within the 26,165 mm ± 10 mm and its surface mapped at 55° elevation, fabrication of the convex test plate began. Using the non-contact test fixture, the convex test plate was figured relative to the known concave master. Once the convex test plate was completed, all subsequent segments were figured to match it. The amount of spherical power (Zernike coefficient $C_{2,0}$) on each segment will be controlled to ±0.19 λ PV after maintaining the nominal air gap spacing between the test plate and the segment. This controls the amount of radius of curvature difference to the 0.5 mm specification. The segment interferometric data will have power, tilt, and the surface error map of the convex test plate removed. The resultant surface error shall be within 0.052 λ RMS to verify the 0.033 μm RMS specification. To ensure optical specifications are met, a redundant test of the first completed segment was performed. Here, an interferometric test was executed at the center of curvature of the segment on its metrology mount at 55° elevation.

4. PRIMARY MIRROR FABRICATION

The optical processing approach that Kodak applies to the HET segments is simple and direct. The elements of Kodak's approach include the following key processing steps: final shaping, pad bonding, polishing, in-process testing, ion figuring, and final testing and certification.

Oversize, hex shaped Zerodur™ blanks are received at Kodak in batches of six. After incoming/receiving inspection a paralleling operation is performed using a large Blanchard grinder. The perimeter of the mirror is shaped using a MAHO CNC mill specially outfitted for glass cutting. The blind radial support hole is milled into the back of each segment on the Blanchard machine using an auxiliary high-speed spindle. The 26,165 mm radius is established on the Blanchard grinder using bound diamond cutters. Fine grinding of the concave and plano surfaces is accomplished on a tub grinding machine using sub-aperture ceramic laps and loose abrasives. Controlled grinding techniques are used to remove the sub-surface damage from the generating operation. The radius of the lap and of the work is carefully monitored by the use of a spherometer. Vacuum lifting fixtures and an overhead crane are used to load and unload the mirrors from the various machines. Polishing of the plano back side of the segments then completes the passivation of sub-surface damage. This operation is completed using a 160-inch diameter planetary polishing machine.

Pad bonding is done next prior to optical polishing to allow correction of any surface errors that may be induced by the shrinkage of the adhesive. The nine 16 mm diameter Invar buttons are cemented into place using Epotek® epoxy. The location of the buttons is controlled using a cementing fixture.

Polishing of the concave surface is performed on a 2.5 m diameter planetary polishing machine (Fig. 3). Here a convex pitch lap is created on a granite table. The planetary table was modified from a standard plano configuration to a convex table with a spherical radius of approximately 26 meters. The radius of the table is controlled by the radial position of the conditioner on the table, the same technique used to control table flatness for standard planetary polishing. Polishing operations continue until all the sub-surface damage has been removed from the surface, and the surface error is small enough to allow for efficient ion beam figuring.

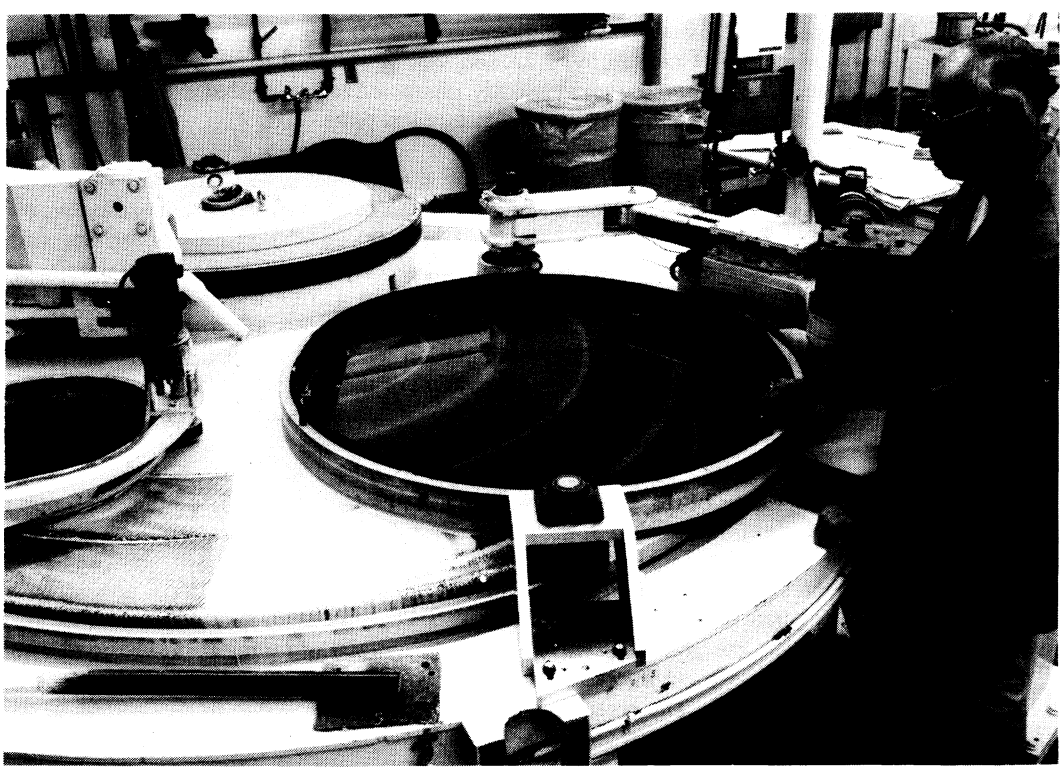

Figure 3. Planetary Polishing Machine

Ion figuring takes place in Kodak's 2.5 m Ion Figuring System (Fig. 4). This process deterministically removes material from the optical surface in a high vacuum environment.[5] One or two parts are loaded with the conventionally polished surface oriented down onto a 4-point support. Support "pads" are positioned at the periphery of the optical surface and safely support the weight of the mirror. The surface departure of the segment prior to Ion figuring includes contributions from the difference in radius (sag mismatch) and deformation because of the effect of gravity on the mirror mount at the 55° elevation angle. Ion figuring efficiently corrects all surface deformations with convergence rates as high as 10 maintaining the surface microroughness specification of 20 Å RMS.

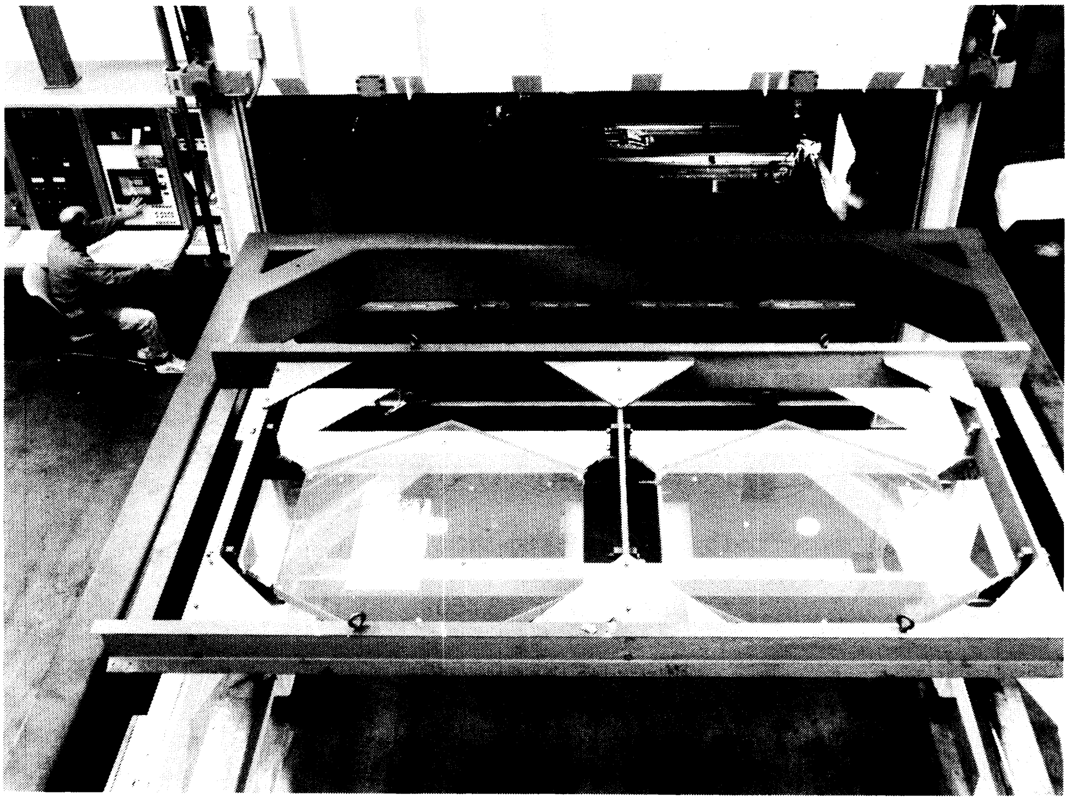

Figure 4. Ion Figuring System

5. ACKNOWLEDGMENTS

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