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Development of a Star Tracker for the Hobby-Eberly Telescope

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ABSTRACT

A large prime-focus robotic star tracking device has been designed and constructed and is now undergoing commissioning atop the 9.2-meter Hobby-Eberly Telescope (HET) at McDonald Observatory in West Texas. The novel, cost-effective tracker represents a major departure in the way very large astronomical telescopes are controlled in pointing, tracking, and guiding. The tracker development and design implementation included detailed structural analysis, the application of minimum constraint kinematic design to a large gantry-type motion control system, and the unique application of a large precision hexapod (Stewart platform) to solve the dynamic tilting and focus motion problems. Challenging fabrication, test, and on-telescope assembly problems were overcome. Performance data of the completed device demonstrate that the tracker design and implementation efforts were successful.

Keywords: star tracker, pointing, tracking, guiding, precision motion control, hexapod, Stewart platform, prime focus instrumentation

1. INTRODUCTION

The HET is a joint project of The University of Texas McDonald Observatory, The Pennsylvania State University, Stanford University, Ludwig-Maxmilians Universität München, Germany and Georg-August-Universität Göttingen, Germany. The project encompasses the design and construction of a modified Arecibo-type telescope, using an array of 91 1-meter hexagonal mirror segments to form a 10-meter diameter spherical Primary Mirror. The telescope operates at a fixed elevation of 55 degrees, and is rotated and set in azimuth position prior to observation (Fig. 1). Astronomical objects are acquired and tracked through the motion of the tracker carrying the payload along the prime focal surface at the top end of the structure.

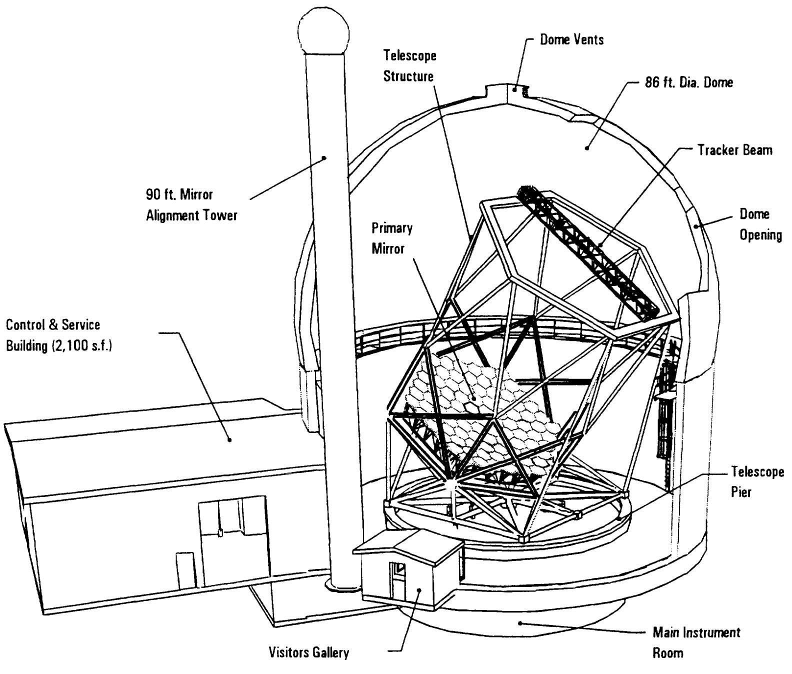


Figure 1 - HET Facility

2. BACKGROUND

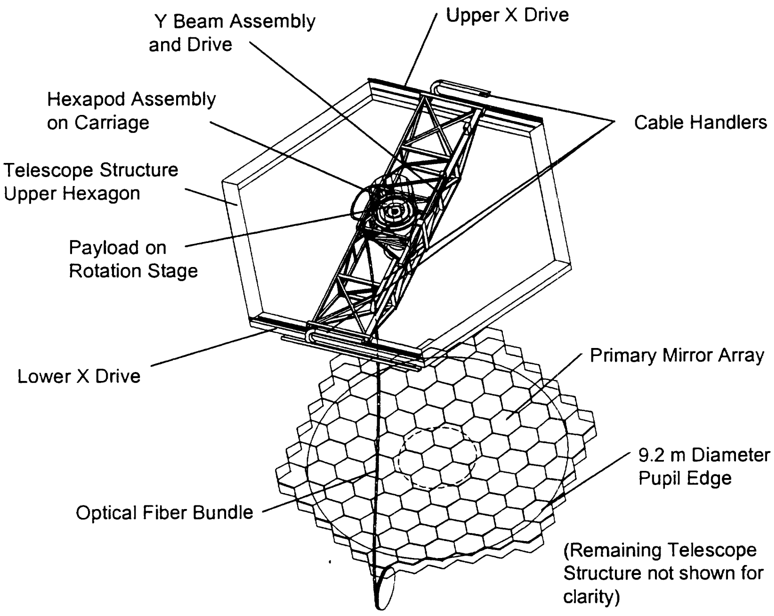
2.1 General

A conventional telescope points at a star by physically aligning the optical axis of its primary/secondary mirror system with the star. The telescope then tracks the apparent motion of the star due to Earth's rotation by moving its primary and secondary mirrors and their support structure in unison to maintain optical alignment with the object. The image is fixed with respect to the telescope structure and can be acquired and observed for long periods of time by instruments bolted to the telescope.

For very large telescope primaries, maintaining the mirror's exact figure while tilting it to point to and track astronomical objects all over the sky becomes technically challenging and expensive due to the changing gravity vector on the mirror. The drive system required to move such a structure over large angular travels is also expensive, in that it must control to sub-arc-second precision the motion of many tons of telescope support structure and primary mirror for long periods of time.

2.2 HET concept

The HET was originally conceived of as a large but inexpensive survey instrument that would by its design eliminate the problems associated with changing the primary mirror's zenith angle (and thus its position with respect to the gravity) during an observation. The segmented spherical primary mirror is installed permanently at a fixed zenith angle, in this case 35°, and creates a useable focal surface (shaped like a giant contact lens, convex downward, and commonly called "the focal sphere") about 4 m in diameter at a distance of 13 m from its vertex. When the mirror is exposed to the clear night sky, this shallow surface represents a 17° diameter circle of astronomical real estate. A relatively lightweight 6-ton tracking assembly follows the star images, rather than the entire 80-ton telescope structure. The tracking assembly, or tracker, is shown mounted to the telescope structure upper hexagon in Fig. 2, below. Since the mirror has a spherical figure, corrector optics in the payload are needed to control spherical aberration and coma in the image. The image is then routed either to a 30-m optical fiber leading to medium-and high-resolution spectrometers (Horner *et al.*[1], and Tull[2], respectively) situated in the facility's temperature-stabilized basement, or to the on-board low resolution spectrograph, currently nearing completion and discussed in Hill *et al.*[3].



Other benefits accrue as a result of this novel design concept as well. The primary mirror segment axial and radial support systems are simplified. Mirror segments are all identical in figure and easy to fabricate. The dome and its supporting ring structure can be significantly smaller than a conventional structure housing the same aperture telescope. A full zenith-to-horizon slit opening outfitted with adjustable wind screens is not needed in the dome, further reducing cost. Initial experience with the implementation of this design is detailed in Ramsey *et al.*[4] and Glaspey *et al.*[5]

2.3 Tracking motion

An easy way to picture the required motion of a tracking device for this telescope is to imagine that the telescope is pointing due south, and that one is on the catwalk visible in Fig. 1, behind and above the primary mirror, looking out the open dome at the dark West Texas sky. Since McDonald Observatory is in the northern hemisphere (30°40' N. latitude), the stars would appear to be moving from one's left to one's right across the 12-m dome aperture. The primary mirror forms the large sky image, inverted and reversed, at the level of the structure's upper hexagon Since the telescope mirror is fixed while in use, the star images in this enormous field move across the top of the telescope in the opposite direction from their apparent motion in the sky, that is, from one's right to one's left.

The way a single star illuminates the useable area of the primary mirror is shown in the figures on the following page. As the star is acquired (again, telescope pointing south) at the eastern edge of the tracker's field of view, the tracker, shown without its normal payload, will be in the position shown in Fig. 3. The effective pupil (white circle) moves across the primary mirror until the star reaches the western limit about 60 minutes later, as shown in Fig. 4. The inner and outer diameters of the pupil are determined by the spherical aberration corrector optics within the tracker payload. The tracker shadow can be seen on the filled-in mirror array in Fig. 4.

In the south, the linear speed of the images moving along the focal sphere is about 1.3 mm/s. In the north, although the sidereal rate is of course the same in angular terms, the linear rate slows to about a third of the southern rate due to the apparent compression of Right Ascension as the northern celestial pole is approached. In terms of tracker coordinates, horizontal motion is along the X axis, and motion perpendicular to this axis in the plane of the upper hexagon is along the tracker's Y axis, parallel to the structure-spanning beam.

There are 4 additional motion axes required to accurately track astronomical images formed by the primary mirror. Since the images travel along a shallow spherical focal surface which is convex downward, there is also a component of required payload motion along the telecentric optical axis (Z), as well as about two tilting axes, Theta (rotation about X) and Phi (rotation about Y). At the center of the primary mirror, the Z motion is equivalent to focus. The tilting axes are required to keep the optical axis of the payload normal to the primary mirror. The last axis, Rho, is necessary to "derotate" the rotating sky image (again because the primary mirror is fixed), and to orient the payload instrumentation with respect to non-rotationally symmetric astronomical objects (*e.g.* comets, elliptical galaxies).

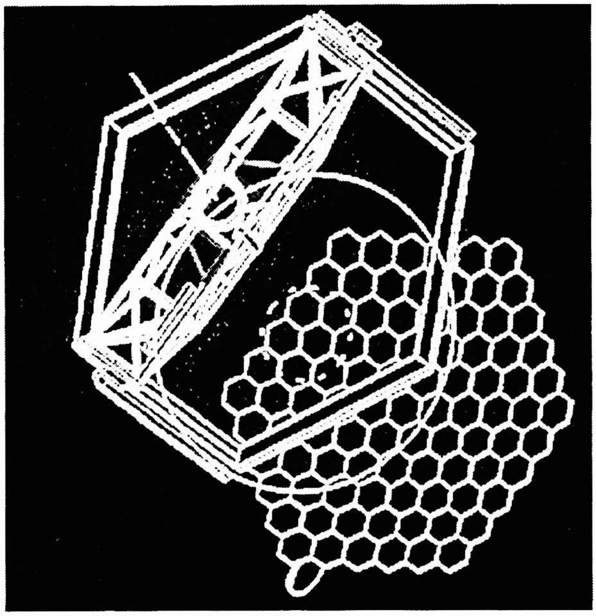


Figure 3
Acquiring object in the east, telescope structure pointing south

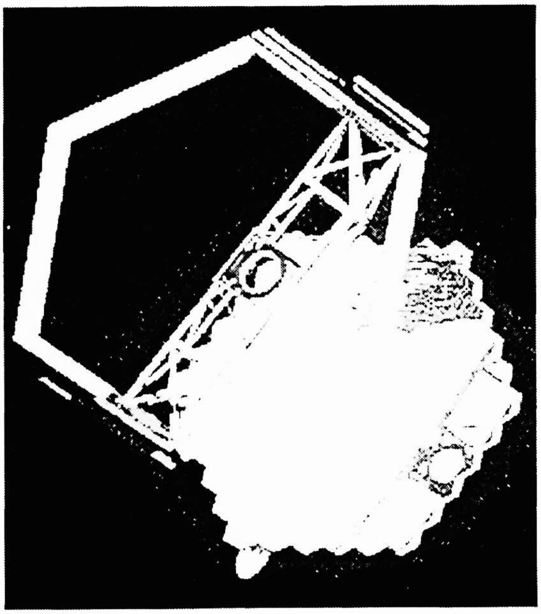


Figure 4
End of track in west, telescope structure pointing south

3. DESIGN DEVELOPMENT

3.1 HET Project design development overview

The HET Project underwent a long phase of early concept design from its inception in the early 1980's until 1992 when significant project funding became available. Many of the basic concepts developed during this early period remain in the executed design. Many more were changed beginning in 1992 to afford a practical design that could be built with budget. Following the section below, the final design requirements extracted from the science requirements are summarized.

3.1.1 Early concept work

In the original HET designs at Penn State, zenith angle was 20 degrees and the tracking range covered a 4 degree square on the sky. Science requirements for the tracker were more attuned to measuring galactic redshifts. The first concepts aligned a pair of simple tracker rails along the projected direction of right ascension in tracker space. The angle of rotation to accomplish this alignment, the parallactic angle, required a polar substage near the tracking sphere.

As the University of Texas and other institutions joined the project, further uses of the telescope's images were specified, and the zenith angle grew to 35 degrees. At the same time the tracking range was defined over a square of 6 degrees, at any rotation. When it was decided to map the principal axes X and Y of all trajectories to an XY mechanical stage, without using a rotational substage, the telecentric deviation for the pointing vector grew to about 8.5 degrees. The size of this new square tracking assembly now precluded using standard axes to achieve 2 degrees of tilt, necessary to maintain the corrector optics normal to the primary mirror. The additional spans imposed by larger tracking motion and the beams made necessary by flexure tolerances and pointing specifications began to introduce conflicts with the vignetting limits surrounding the central obscuration and in the illuminated annular entrance pupil.

Two design decisions were proposed to open up the design space. First, a long beam spanning the width of the HET's upper hexagon was thought to offer greater potentially greater design possibilities with less vignetting and obscuration and secondly a tilting mechanism other than independent axes was proposed. The first tilting mechanism identified and examined was a "wobble plate" atop 3 parallel linear actuators. Intrinsic to this mechanism is its orthogonal relationship to the Cartesian system of the tracker space. However, a more functionally flexible mechanism, the 6-legged hexapod, or Stewart Platform, has the ability to program the rotation point with ease.

The hexapod possesses a number of other advantages: It is extremely stiff mechanically, having 6 parallel strain paths; it is relatively lightweight, and it has an open center for insertion of a well-balanced payload. In addition, the design and construction of six identical mechanisms for this assembly leads to economies of scale.

3.1.2 Long beam concept

About 20 design iterations assisted by finite element analysis proved the long beam concept was at least viable enough to suggest to vendors, along with the HET design team's centerlines for the beam's triangulated bridgework. At the ends of the beam, various combinations of end conditions were envisioned, and several different triangulation schemes were tried to improve dynamic performance and static rigidity. The final versions of the beam carrying a theoretical corrector and instrument loading had fundamental modal frequencies of about 15 Hz. Static deflections well within the performance parameters.

3.1.3 Hexapod concept

For the tilting mechanism, various hexapod arrangements were designed and analyzed[6]. Field trips to the robotics laboratory at the University of Texas at Arlington produced further knowledge of hexapod computation and introduced the team to the forward and reverse transforms, the reverse transform being to calculate the leg lengths of the hexapod when given the movable plate's position, and the forward transform being the opposite case. Both are nonlinear, but the forward transform involves the simultaneous solution of at least 3 nonlinear equations, necessary to close the loop about a celestial target. For the particular case of the HET, a symmetrical hexapod geometry allows the eventual development of a straightforward version of the forward transform, but such was not used for the initial open loop tracker software.

The hexapod rides a carriage which runs along the tracker beam. After several design sessions, a design using only one side of the beam as a guide rail evolved, and is the method used to prevent binding of the Y-carriage bearings. The non-guided side simply provides rotational constraint about the Y axis, but is free in the X and Y directions. All constraint in X is done on one rail, and the Y-carriage has wings carrying the guide bearings as long as is possible given the telescope's top dimension and the travel required. The Y carriage forms a deep basket whose bottom plane provides a fixed platform for the 6 linear actuators. The hexapod's upper movable plate carries an instrument rotator whose bearing is custom designed to accept the 3 upper load points of the hexapod. Extensive finite element analysis was used iteratively to improve and refine the Y-carriage basket and hexapod legs.

All equations of motion and a strawman servo design were supplied to the various vendors at the time of bidding. This helped to provide a basis for eventual software engineering for the overall system. Suggested positions for cable wraps, the fiber drape, linear bearings, and motors were established before the bid package was completed. All motion for the tracker may be derived from the telescope's spherical geometry, its orientation on the earth, the sidereal time, and a given ephemeris[7,8].

3.3 Critical design development

In 1992 and 1993 the project received major impetus with the advent of additional funding, the hiring of a project manager, and approval from the University of Texas administration. The science requirements were agreed upon by all partners in August 1993, and the specific engineering requirements and specifications for the telescope's major subsystems were developed from these science requirements. The tracker requirements are summarized in the table below:

Capability	Requirement
Payload capacity	Payload Capacity - 440 kg requirement, 640 kg goal Breakdown: Spherical Aberration Corrector - 90 kg Tracker Optical Package - 150 kg Prime Focus Instrumentation - 200 kg max reqm't., 400 kg goal
Acquisition and tracking range	12° track anywhere within 6° of telecentric axis Translates to 3,900 mm XY travel at 0.063 mm/arcsec Tilt ranges are +/- 8.5° from telecentric axis Rho range is +/- 115°
Pointing accuracy	30 arcsec blind pointing, includes telescope structure 10 arcsec tracker only 0.02 arcsec offset pointing
Tracking accuracy	2 arcsec/2 min, open loop
Minimum structural frequency	10 Hz first mode
Maximum obscuration	3.2% of primary mirror area excluding central obscuration due to corrector optics
Weight	4,230 kg, with minimum payload
Thermal load handling	All motors insulated and cooled, 1000 W additional for payload cooling

Table 3.1 - Tracker Requirements Summary

3.4 Procurement

In the Fall of 1994, the final Statement of Work and Specifications[9] for the tracker were written. The complete HET Project in-house design was detailed in this document for design guidance to the vendor. A great deal of attention was given to this effort in order to present a clear design and specification to the vendor community. The goal was to specify the minimum requirements necessary to design and build a device that would accomplish what was needed, without over specifying or over designing and thereby driving up the cost. The philosophy was that individual designers at the vendor would best know how to accomplish the details of this task within their own environment, without having a detailed design and "build to print" model forced upon them.

Much work was done during the in-house design phase to develop a knowledgeable and qualified vendor base. This work resulted in five qualified proposals for the tracker. The proposals were evaluated by HET engineers on the following basis: Understanding of the problem, 20%; technical approach, 20%; vendor qualifications, 20%; proposed schedule, 15%; and overall comparative value, 25%. The contract for remaining tracker development and construction was awarded to Orbital Sciences Corporation, Chandler, Arizona, January 30, 1995 based on a superior design proposal evaluated using the above criteria. The fixed price contract value was approximately $970 K.

3.5 Orbital Sciences Corporation design development

Orbital designed and built the tracker as a stand alone module of the overall telescope based on the HET Project Specifications and Requirements document. This document defined the tracker design concept, structural requirements specific to tracking, certain required hardware, the electrical and software interface requirements, and the final performance of the tracker. Commercial off -the- shelf (COTS) components were used where possible. This approach reduced design effort, cost, and schedule. As the design progressed many of the originally specified components had to be modified to work in the final design configuration. Some of these changes were due to the overall tracker weight increase from 8,300 pounds to 11,006 pounds. The complete Orbital delivered tracker consists of the Tracking Beam Assembly, the X Drives, Electronics Cabinet, software and control. Orbital and the HET Project team worked closely together during the design, construction, and test to modify the design and requirements of the tracker in order to provide the best instrument possible within the scope of the contract.

3.5.1 Design and analysis

The main mechanical components of the tracker are the X drives, the Y Beam assembly, Hexapod, and the Rotation Stage (Fig. 2). Where possible, the design and analyses effort were divided into these major assemblies. The other major components are the software, control system, and electrical system.

3.5.2 Y Beam and Carriage design

A major challenge of the tracker design was to meet the 8,300 pound total weight and stiffness requirements for the Y Beam and Carriage assembly. The stiffness was not only driven by the 10 Hz minimum Y Beam frequency requirement, but also static and wind loading deflections. Usually stress considerations are secondary when designing for stiffness, but the Y Beam and Carriage required detailed stress analyses using finite elements and classical techniques due to the weight constraint. Orbital typically designs to a minimum safety factor of 2.0 to yield. All welds were analyzed to ANSI/AWS D1.1-92 standards.

The weight of the Y Beam assembly and Carriage assembly account for 68 % of the total tracker weight. This large weight percentage drove the Y beam and Carriage design to thin wall rectangular steel tube welded construction. Initially the HET concept Y beam was modeled to determine the frequency and deflections. The design would not meet the requirements. A new design was created using larger cross-section tubes. The design was iterated between stiffness and stress with weight and obscuration always checked as constraints. An example of trade-offs during iteration is a plate was welded to the Y drive side of the beam to increase the stiffness but keep the weight lower than adding a thicker wall tube. As the model was iterated more detail was added to determine the cause of low frequencies. As shown in Table 3.2, the final Y Beam and Carriage design met all structural requirements.

Requirement	Final Design
Minimum Structural Frequency $\geq$ 10 Hz	11.53 Hz
Self Weight Deflections $\leq$ 0.080 inch	0.039 inch
Wind Deflections $<$ 0.0007 inch	0.0007 inch

Table 3.2 - Structural Requirements / Final Design Values

3.5.3 Y drive

The Y axis incorporates two parallel bearing sets mounted to the Y beam for the Y carriage to move on. As shown in Fig. 2, one side of the carriage is driven by the Y Drive. The design of the Y Drive is the same as the X Drives. By standardizing the drives the overall cost was held down and system logistics simplified. The drives use a dual motor system and an SKF roller screw. The roller screw is a planetary, preloaded flange nut design with a 0.236 inches (6mm) lead and 6 thread starts. The original screw diameter specified in the requirements could not be manufactured in the final design length of 200.48 inches (5092.2 mm). The manufacturing requirements drove the screw diameter to 2.207 inch (56 mm). Orbital worked closely with SKF on the design of the screw.

The dual drive motor concept was defined in the original specification. One drive motor for slew and one for tracking. Orbital investigated using a single direct drive motor for both functions. The results showed a direct drive torque motor with a tachometer could work. To reduce risk we decided to err on the side of conservatism and use the dual drive system. The drive includes two spring loaded fail safe pneumatic brakes. One for the slew drive and one for the track drive. The brakes are used as a clutch as well as for braking. The slew brake is applied during tracking and track brake is released. The opposite is done during slewing. The track motor uses a COTS 50:1 harmonic drive and motor tachometer assembly. The drive is coupled to the roller screw using a standard double flexing coupling. The track motors are cooled using coils wrapped and potted on the motor / gear case. In order to provide high stiffness and a compact mounting the shaft bearings used are ball screw support bearings. These bearings are standard designs in matched sets with high preload. The low shaft speeds allowed the use of these bearings. The slew drive is an uncooled direct drive torque motor. The motor was sized based on the Y drive loads. Unfortunately the motor was not designed to the catalog motor specifications. The motor was over driven twice during testing and finally had to be resized. The resized motor has yet to be installed. The slew motor and high preload duplex bearings are mounted to roller screw nut through precision stub shafts.

The linear bearings used on the Y axis are standard THK bearings. The drive side bearings are larger than the non drive side due to the higher loads. The rails on each side are manufactured in three sections. The bearing size had to be increased from the concept design.

The Y carriage position is measure using a linear encoder manufactured by Heidenhain. The encoder read head is mounted to the carriage at the drive attachment to reduce errors in measurement due to flexure of the Y carriage. The encoder must be assembled and calibrated on the structure because of its length. The same encoder is used on both X drives.

3.5.4 Y Carriage assembly

The Y Carriage assembly consists of the welded carriage, hexapod, and rotation stage. The original design concept for the carriage was used. A three point semi kinematic mounting scheme was used. The Y drive side incorporated two pairs of linear bearing blocks separated by 106 inches. The Y non drive side of the carriage has one bearing block attached to a cross axis (X Direction) linear bearing. This concept decouples the non drive linear bearing from the drive side linear bearing. The rest of the carriage design was described with the Y beam.

3.5.5 Hexapod

The hexapod is comprised of six struts that are combined in pairs (bipods). The lower end of each strut pair is attached to a fixed frame (the Y carriage) in a specific geometry. The upper end of the strut pair is joined through bearings to each other. This single interface point is attached to the hexapod moving frame (rotation stage plate). There are three interface points, one for each bipod. The plate maintains the upper strut ends in a fixed relationship to each other as the hexapod moves the plate through six degrees of freedom.

The original hexapod geometry layout incorporated three different strut lengths. The first task was to generate a geometry that would require only one strut length for all six struts. The pattern of the hexapod fixed and moving mounts were adjusted to create six identical struts. The kinematic equations of the hexapod were verified for this configuration. Identical struts reduced the design and manufacturing costs as well as simplifying the logistics of the system. Once the configuration was finalized a clearance study and kinematic/ kinetic analyses were performed. The clearance study was done graphically to check for any interference with the surrounding structure. A completely mechanical solution was not practical to implement to prevent the hexapod from impacting the surrounding Y carriage structure. The final system required software limits to prevent out of envelope commands from driving the hexapod into the carriage. The kinematic / kinetic analysis was performed using Applied Motion modeling software. The velocities and rotations were verified. A key output from the analysis was the strut loads. Ideally the strut loading should not reverse sign during any required motion. This requirement eliminates uncontrolled jumps in the motion due to axial stiffness or clearances. The strut is essentially preloaded in the same direction throughout the motion. The analysis confirmed the design did not have load reversals.

The mechanical design of the strut incorporates a standard 1.574 diameter x 0.197 inch lead (40 x 5 mm)ball screw with preloaded nut. The screw shaft was manufactured to Orbital specifications for the shaft ends. The fixed and moving ends of the struts are attached to there respective mounts using standard precision tie rod ends.

A single drive motor was desired for the strut. Using a single motor and drive train created a design and control issue due to the large dynamic range required for tracking to slewing. This requirement was not a problem on the X and Y drives due to the dual drive design. To make the hexapod compact and simple and single drive motor was desired. The drive system chosen incorporates a COTS stepper motor with micro stepping control and a modified worm and gear set. Drive resonance's were first eliminated as much as possible through adjustable preload capability on the worm. Then any remaining resonance issues were removed in the control system tuning.

The defining equations of hexapod motion are based on strut lengths. To reduce measurement errors and to more directly determine the inputs required by the control system a linear encoder is used to measure the change in strut length. The encoder is manufactured by Heidenhain. This encoder is assembled and calibrated when manufactured. There is one encoder per strut.

3.5.6 Rotation stage

The rotation stage is attached to the moving plate of the hexapod through a plate. The plate was designed for stiffness. The plate provides the mounting for rotation drive and rotation bearings. The bearings are a unique design from THK. The bearing is essentially a linear bearing rail formed into segments of an arc. These segments are jointed to provide continuos rotation. The bearings were specified in the concept design. Three bearing blocks are used on for the stage. The blocks are fixed to the plate directly above each hexapod bipod joint. Therefore the loads are transferred directly into the bearings and the hexapod struts without induced moments. The bearing rail is attached to the rotating stage. The stage is a large machined aluminum rolled ring forging. The tracker payload (telescope secondary) is attached to the stage. The stage is driven through a cable drive system designed by Sagebrush Technology using an Orbital specified drive motor. The drive motor is a Compumotor Dynaserv. The drive uses a patented capstan and cable arrangement . The capstan is directly attached to the Dynaserv motor. Ten cables are looped around the capstan and attached to the rotation stage. The position of the stage is measures directly using a Heidenhain LIDA 360 tape encoder attached to the rotation stage.

The motor is wrapped in cooling coils and the assembly is insulated. The drive was tested and verified at Sagebrush prior to delivery to Orbital. The drive provides stiffness of 10 x 10^7 in-lb/rad.

3.5.7 X drives and Y beam skew mechanism

The tracker concept incorporates two sets of X Drives, an upper and lower drive, for the Y Beam assembly (See Fig. 2). As described in the Y Drive section, the X Drives use the same components. The X axes use the same Heidenhain linear encoders as the Y drive. The linear bearings are a larger size. The bearings are also manufactured by THK. The upper and lower X linear bearings were increased in size from the concept design. Due to the length of X travel the bearing rails were provided in two sections for each X axis drive. The tracker specification required the rail pairs to be butted together and ground to insure a smooth transition at the joint. This requirement forced the rails to be custom manufactured at THK in Japan. All bearing blocks were specified to be of an interchangeable design to facilitate maintenance. A few of the blocks did not function as desired and were replaced with stock blocks. The performance of the blocks was acceptable on the existing rail. Moment loading of the bearing blocks turned out to be a major concern in the design. A detailed analysis, including the bearing stiffness, was performed to determine the actual loading on the blocks. This moment loading drives the life calculations of the bearings.

The connection between the X drives and the Y Beam assembly is through a skew mechanism. The original concept was to use flexure plates to suspend the Y beam at the X drive interface. This concept appeared to have too many unknowns in it. The suspension could drive the required tracker frequency and wind deflections, extensive analyses were expected to define the flexure. Orbital's approach was to simplify the skew mechanism by using standard parts and reduce risk due to possible redesign during integration. The first approach was to use standard flex pivot bearings. These are well defined and commercially available. Unfortunately bearings large enough to carry the loads created when the Y beam was installed at 35 to horizontal are not available. It should be mentioned that the upper X drive is decoupled from the Y Beam assembly in the Y direction by the use of short linear bearings. This is the same semi kinematic mount scheme used for the Y Carriage. Therefore all the loads to keep the Y beam from sliding off the telescope are carried by the lower X skew mechanism and linear bearings. The next and final choice for the skew mechanism was to use a standard turntable bearing on the lower and upper X axes. The bearings are compact, can be preloaded, the torque can be characterized, and they carry large loads. A skewed condition is determined by two proximity sensors on the lower X drive. One senses a small skew condition and gracefully shuts down the system. The second is a fail-safe that cuts power to the system and applies the fail-safe brakes.

3.5.8 Cooling and pneumatics systems, cable handlers

All motors on the tracker, except the three slew motors, are liquid cooled. As described earlier, the motors were wrapped in copper tubing and then potted. There are shut off valves for each major module to allow for disassembly without draining the complete system. The coolant to be used on the telescope is a water / glycol mixture.

All brakes, except for the rotation stage, are pneumatically operated using regulated, filtered shop air. Igus cable handlers were specified by the HET Project for all axes. Trays were designed to support the handlers during travel. The Y axis cable handler was mounted on supports above the Y beam to maintain the tracker low obscuration requirement (See Fig. 2).

3.5.9 Electrical design and development

Orbital designed the electrical interface of the tracker to the telescope electrical system. Flexibility of cabling used for the tracker was a design issue. The larger power cables required special cable design to work in the cable handling systems. Line loss of signals from the encoders and tachometers were also an issue. The Heidenhain LIDA 360 required a custom built amplifier on the hexapod to ensure the signal would reach the interpolating electronics in the rack. Two sets of limit switches were used on each axis at both ends of travel. The first provides a graceful shutdown. The second will cut power and requires a manual over ride to move the tracker in the axis that has tripped the fault. Manual emergency shutdown capability was also provided.

3.5.10 Control and software design and development

Orbital did the detailed control system and software design for the tracker. Tracker control system and telescope interface software is run on a 486 computer. The Lynx real time operating system was specified by the HET Project as the interface between the Telescope Control System (TCS) and Tracker Subsystem (TS) computer. The software interface to the TCS from the TS computer was defined as a joint effort with the HET Project team. The TS accepts tracking commands from the TCS in tracker space coordinates. The TS then converts the coordinates to actuator space coordinates for required actuator motion. Multiple status windows are available. These can be requested form a remote location, the control room, or at the tracker computer. The interface provides data monitoring, error and status to the TCS. The interface allows trajectory and asynchronous corrections from the TCS. The TS Lynx operating system also must provide the interface to the control electronics. The local display provides more detailed information on the tracker status such as operating parameters, time, individual actuator command and response.

The software also provides the capability of generating a mount model for each axis. The mount model coefficients are determined by an external measurement and input into equations in the software. The equations can be linear or higher order polynomials.

The control electronics for the tracker were specified to be Delta Tau PMAC. This requirement provides commonality among the various control systems at the telescope. The system required control of thirteen motors, seven brakes, and limit switches on all axes including each hexapod strut. The Orbital design procedure was to first model the control system using Matlab and other methods to define the gains and filters required. The controls engineer was constrained somewhat by the use of the COTS components. These values were then input into PMAC and the system was tuned during integration. The final values for the constants were then input into an initialization file and downloaded into the PMAC from the TS at start up.

4. CONSTRUCTION AND TEST

4.1 Construction

Orbital completed all the drawings and specifications to fabricate the tracker. The fabrication is contracted out to various machine shops with Orbital oversight. The Y beam and carriage were large weldments that required precision machining. Plates and bars were welded to the tube structure to provide stock to machine the bearing mounts, motor mounts, encoder mounts and other surfaces. Warping of the structures during fabrication and over time were a concern. Due to large size and thin tubing used heat treatment in an oven was ruled out for the Y beam and the carriage. A vibratory stress relief process was specified for these structures. Orbital has successfully used this process on large rail launchers we designed. The Y beam bearing rail mounts required a very long precision machined surface. This machining was done using a portable mill mounted on rails that ran along the length of the Y beam. The rails were aligned using a laser leveling device loaned to Orbital by the HET Project. This laser level turned out to be very useful in the manufacture, installation and testing at Orbital. The majority of the tracker is fabricated from A36 structural steel. The Y beam and carriage were painted with low reflectivity paint. Smaller structures were painted with a flat black.

4.2 Integration and test

The tracker was built and integrated in one of the high bays at the Orbital Chandler facility. The tracker required final integration and acceptance testing in the installed configuration of the Y axis at 35° to the horizontal. The Y beam is approximately thirty five feet long. Therefore to simulate the telescope mounting the upper X axis was over thirty feet from the floor. The upper and lower X axis beam design used on the of the telescope were fabricated and installed on the test stand. The assembled test stand now simulated the upper hexagon of the telescope.

The modules were first assembled and tested in a horizontal configuration. The modules were wired and electrically checked using the deliverable cables. Each hexapod strut was assembled and tested. Then the hexapod and rotation stage were assembled on the carriage and tested. The Y carriage bearings were installed on the Y beam. The carriage and Y dive were then attached to the bearings. The X Drives and bearings were mounted on the test stand beams. All the drives were aligned with the linear bearings using a theodolite as an alignment telescope. The bearing mounts were adjusted into alignment using prefabricated shims. Each axis was tested in the horizontal unloaded condition. The Y beam Assembly was lifted onto the X drives using the overhead crane in the bay. The Y beam was then lowered straight down onto the X drives interface. The interface is the skew bearings.

A system acceptance test plan was define by the HET Project and the Orbital team. Individual axis performance tests were fairly easy to define although the hexapod required creative effort. Each axis performance was measure first by verifying the encoder accuracy using the laser interferometer. Then the track and slew velocities were verified. The hexapod tracking accuracy was measured using the laser level to generate a line and mounting the read head on the payload simulator. The hexapod was command along a parallel line and the deviation measured. The rotation stage was checked for runout and position accuracy.

The overall system test was difficult without the benefit of the tracker being mounted on the telescope. A plan was devised to survey in a plane that was skewed with respect to the tracker XYZ coordinate system and set up the laser level to define the plane. This test would exercise the X,Y, and hexapod motions. A simple mount model was required to remove cross axis coupling from the motions. The results of the individual axis tests and the system level tests met or exceeded all of the tracker requirements. The combination of the results of these tests assured the Orbital and HET Project team the tracker would function correctly when installed on the telescope.

5. INSTALLATION AND TEST

5.1 Delivery and staging

Following final acceptance testing at the Orbital Chandler facility, the tracker was disassembled, its components carefully labeled, packaged and crated. The tracker Y beam and over twenty large crates were shipped to the HET site at McDonald Observatory in far West Texas, 16 miles north of Ft. Davis. The trucks carrying the tracker arrived on site the morning of September 25, 1996, and were driven slowly up Mt. Fowlkes to the HET facility at the summit. Fortunately during this phase of the project the large spectrometer room forming the basement of the telescope building was empty and available. The Y beam and crates were unloaded into this area, and this became the staging and assembly location for most of the tracker. On-site re-assembly of the tracker took 7 weeks.

5.2 Y drive installation

The initial task was to install the Y drive system, which controls the carriage motion up and down the slope of the tracker Y beam. Alignment of the 4.5 m long Y roller screw with the Y linear bearings to better that 25 microns end-to-end was required. The process was iterative, using the Y roller screw nut surrounded by the slew motor as a guide. After initial alignment, the torque required to rotate the nut/slew motor assembly was measured at different points along the Y screw, and appropriate adjustments made. Following this precise mechanical alignment, electrical check-out and motion testing of the Y track and slew systems was performed.

5.3 Hexapod and Rho stage installation

The hexapod was shipped as three bipod assemblies, which could simply be screwed into the tilting base ring from below once the ring was suspended. The crane in the dome enclosure above the spectrometer room was used to suspend the ring via a strap through the central pintle bearing hole in the dome floor. Once the hexapod bipods were attached to the base ring, the assembly was lifted to the spectrometer room ceiling, the Y beam rolled underneath it, and the hexapod/base ring assembly was lowered into the carriage and bolted on.

5.4 X stage installation

X rail and trolley installation on the telescope structure proceeded in parallel with assembly of the Y drive, hexapod and Rho stage assembly in the basement. X encoder installation followed completion of X trolley installation, using the trolleys as alignment guides. Finally the X roller screws were hoisted into place and aligned with the trolleys following the same procedure use for Y drive alignment.

5.5 Tracker lift and final installation

On the afternoon of November 11, 1996, the tracker Y beam assembly was rolled out of the spectrometer room and lifted to a staging position just outside the dome by the installation crane. The next morning, the tracker was lifted into place on the X trolleys atop the telescope structure. The lift went very smoothly and was completed in about one hour. Full electrical and mechanical check-out and test then became the focus of activity for the next month.

5.6 First light

First light was achieved early the morning of December 10, 1996. Angular alignment of the payload with the primary mirror was marginal, and had to be tuned "on the fly" initially. Nonetheless, first light was an enormous milestone for the project, demonstrating that all of the sub-systems comprising the telescope functioned properly at some level.

5.7 Troubleshooting phase

Following first light, the tracker effort entered a several months long troubleshooting phase in which a host of problems were addressed and ultimately resolved. We experienced numerous amplifier faults within the tracker electronics, due to various hardware and software problems. The faults hampered our ability to perform other functional tests of the tracker. The sources of these faults were determined and eliminated one-by-one. Amp faults on the tracker are now a rarity.

Pointing accuracy was measured in arc minutes initially until we understood and had characterized the support rail geometry and trajectory generation assumptions. Tracking was fair in some parts of the sky (0.01 arcsec/s), and much worse in others (0.1 arcsec/s) in the early stages of operation.

6. CURRENT PERFORMANCE

6.1 General

Since September of 1997, the tracker has been a robust performer. The most serious software and hardware bugs have been fixed, and the telescope operator can with confidence point the telescope and track to the accuracies described below.

Loss last year of the Y slew motor due to overheating has hindered alignment work on the primary mirror until recently. The tracker beam blocks some of the mirror segments from the alignment instrument located at the mirror center of curvature during alignment, and the beam must be moved along the X rails from one side of the telescope to the other to complete the alignment routine. The X slew system was re-enabled in February 1998 to eliminate this problem. A new, more powerful Y slew motor is now in hand, and will be installed as time and other activities on the telescope permit.

6.2 Pointing performance

Blind pointing of the tracker at any accessible target is now about 11 arcsec. The original specification called for 30 arcsec. We believe that pointing can be improved, perhaps to the 1 arcsec level, with additional alignment, modeling and testing. Pointing is not currently constrained by any fundamental limitation of the system (*e.g.* encoder resolution, thermal stability). The pointing improvement effort was halted in September 1997 to focus resources on other aspects of the project, once a functional level of pointing had been achieved.

6.3 Tracking performance

Tracking is currently characterized at the 0.010 arcsec/s level, worst case. As with pointing accuracy, this level of tracking performance has been found to be acceptable for the present, and the HET Project team has turned its attention to other areas for the time being. We hope to return to this problem over the course of the next year as time permits. In principle, given the prime focus image scale of about 0.063 mm/arcsec and the 0.002 mm resolution of the long encoders, we should be able to achieve tracking about one order of magnitude better than is presently possible. Again, additional modeling and test time is required. For now, only occasional guiding is needed during long exposures.

Windshake has not been noticed as problematic based on observer impressions of the many images take thus far. We have not yet done appropriate quantitative studies (trail plates and the like) to quantify or detect the effects of windshake.

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8. REFERENCES

1. Horner, S. D., Ramsey, L. W., 1998, “Hobby-Eberly Telescope medium-resolution spectrograph and fiber instrument feed”, S.P.I.E. Vol 3355, *Optical Astronomical Instrumentation*, (in press).
2. Tull, R. G., 1998, “High-resolution fiber-coupled spectrograph of the Hobby-Eberly Telescope”, S.P.I.E. Vol. 3355, *Optical Astronomical Instrumentation*, (in press).
3. Hill, G. J., Nicklas, H., MacQueen, P. J., Tejada, C., Cobos Duenas, F. J., Mitsch, W., 1998, “Hobby-Eberly Telescope low resolution spectrograph”, S.P.I.E. Vol. 3355, *Optical Astronomical Instrumentation*, (in press).
4. Ramsey, L. W., Adams, M. T., Barnes, T. G. III, Booth, J. A., Cornell, M. E., Gaffney, N. I., Glaspey, J. W., Good, J. M., Fowler, J. R., Kelton, P. W., Krabbendam, V. L., Long, L., Ray, F. B., Ricklefs, R. L., Sage, J., Sebring, T. A., Spiesman, W. J., Steiner, M., 1998, “Early performance and present status of the Hobby-Eberly Telescope”, S.P.I.E. Vol. 3352, *Advanced Technology Optical/IR Telescopes* VI, (in press).
5. Glaspey, J. W., Adams, M. T., Booth, J. A., Cornell, M. E., Fowler, J. R., Krabbendam, V. L., Ramsey, L. W., Ray, F. B., Ricklefs, R. L., and Spiesman, W. J., 1998, “The Hobby-Eberly Telescope: Commissioning Experience and Observing Plans”, S.P.I.E. Vol. 3349, *Observatory Operations to Optimize Scientific Return*, (in press).
6. Schmidt-Kaler, Th., "The Hexapod Telescope: A New Way to Very Large Telescopes", *Proceedings of ESO Conf. on Progress in Telescope and Instrumentation Technologies*, Garching, April 1992, M.-H. Ulrich, ed.
7. Ray, F. B., “HET setting and tracking analysis”, McDonald Observatory technical report TR940301, latest revision 9 Sept. 1997.
8. Ray, F. B., “Tracker mechanism kinematics, servo, and top-level software design for a semi-transit telescope with fixed spherical primary mirror”, McDonald Observatory technical report TR940104.
9. Booth, J. A., 1994, “Statement of Work, Hobby-Eberly Telescope Tracker”, HET document number JAB94-065.