CHARA TECHNICAL REPORT

NO. 9 24 JAN 1995

Telescope Design

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1. INTRODUCTION - THE CHARA ARRAY

The Center for High Angular Resolution Astronomy (CHARA) of Georgia State University will build a facility for optical/infrared multi-telescope interferometry. This facility is called the CHARA Array. The facility will consist of seven (initially five - see below) telescopes, with evacuated pipes conducting the beams to a central laboratory. The laboratory will contain optical delay lines, beam combination optics, and detection systems. The facility will consist of these components plus the associated buildings and support equipment. The CHARA Array is partially funded by the National Science Foundation and will be located on a mountain site in the southwestern United States.

2. OVERVIEW OF THE TELESCOPE SPECIFICATIONS

The CHARA Array telescopes will be single-purpose instruments whose essential function is to feed high quality beams to fixed foci in a central beam combination laboratory. As the beams will be combined interferometrically, the outstanding requirements for the telescopes are mechanical stability and image quality. Almost all other performance characteristics can be traded against these essentials.

The telescope specifications are described in detail in Technical Report No. 8, *Telescope Specifications*, available in this series.

3. THE ENGINEERING DESIGN TEAM AND DESIGN PROCESS

Based on initial contacts with vendors during the planning of the CHARA Array, it was determined that it should be possible to obtain telescopes within the scope of the CHARA budget. However, there was a clear indication that most vendors were inclined to adapt existing telescope designs rather than to develop an optimized design. It also appeared that it would become very expensive to ask vendors to design telescopes to our optical and vibration specifications. Therefore it was determined to carry out the telescope design

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under a consulting arrangement. While the optimized design will require a non-standard telescope, possibly increasing manufacturing costs, it is hoped that by bringing the engineering responsibility within the project, a significant reduction in net telescope cost will be achieved.

The telescope engineering and design is being carried out by L. Barr, supported by engineering and technical staff of the National Optical Astronomy Observatories (NOAO) working under contract to CHARA.

A CHARA committee of the whole monitors the design progress and advises Mr. Barr on cost/performance tradeoffs. Dr. S. Ridgway of NOAO, also under contract to CHARA, works closely with Mr. Barr and provides continuing scientific oversight on a day to day basis in Tucson.

A CHARA Technical Advisory Committee, consisting of technical experts from the interferometry community, will review the telescope design when the layout is complete (January), and again when the structural analysis results are available (March). Structural analysis work has recently been started to enable an iteration process between the telescope designer and the structural analyst.

At present, it is expected that the design team will carry the design only through the layout and analysis stage. It is not currently planned to produce shop drawings. However, this decision may be reconsidered if appropriate resources may be purchased at NOAO on the required time scale. If shop drawings are produced at NOAO, vendors will then be able to bid on a "build-to-print" basis which further removes engineering responsibility from the vendor and allows vendors without an engineering department to submit a bid. In most instances, this will result in a lower bid, however, this tactic also removes the opportunity to adapt parts for easier fabrication at the vendor's facility which can have the opposite effect. Moving further in the direction of completed shop drawings will progressively reduce the cost to CHARA of the telescope fabrication, but will also progressively increase CHARA's responsibility for the correct functioning of the finished product. This is a path which will be followed with caution.

4. OVERVIEW OF THE TELESCOPE DESIGN

The layout of the telescope design is shown in Figure 1. The mount is an altitude-azimuth type. The most prominent features of the layout are the azimuth yoke and optics support structure which rotates about the altitude axis and will hereafter be called the "tube" despite its relatively open configuration. The tube is mounted outboard of the azimuth axis in order to eliminate two reflections within the telescope and mount compared to a more conventional coudé system. The yoke is asymmetric to maximize rigidity against vibration and wind shake. The elevation axis is located at the center of the tube in order to minimize dome size (a major cost driver), maximize rigidity of the tube, and minimize shake due to wind buffeting (assuming that the wind will blow equally on both the upper and lower ends of the tube). More detail is provided in the section on the Telescope Mechanical Mounting.

5. OPTICS

For the CHARA Array we wish to take advantage of modern telescope technology when possible to obtain performance and cost benefits, but owing to the limited budget it is not

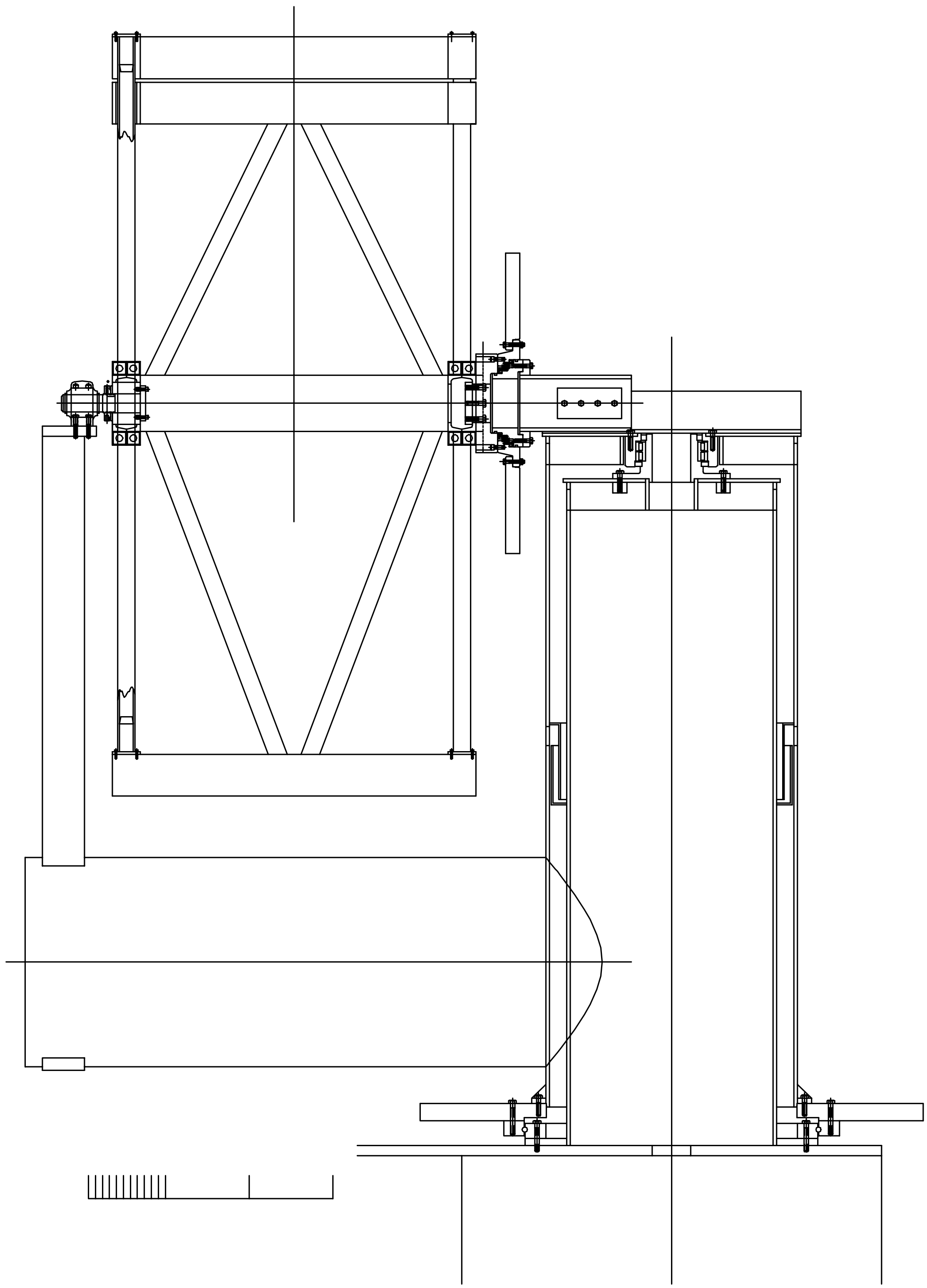

FIGURE 1. Telescope layout. The scale at the lower left is three feet long.

possible to venture into developmental or risky materials or methods.

5.1. The Optical Design

The optical design for the CHARA telescopes is described in the document *Optical Layout and Error Budget for the Telescope, Catseye and Compressor of CHARA*, by Liang Ming of NOAO. The optical design analyzed is an aplanatic afocal system consisting of confocal paraboloids.

For cost and stability reasons it is desired to keep the telescope short. However, very fast optics are expensive and impose severe mechanical tolerances. The design and tolerances were investigated for f/2.5 and f/2.0, and vendors were queried about the availability of optics in this range. It was clear that f/2.5 would provide most of the advantages of compactness, whereas f/2.0 would lead to excessive optics cost. Therefore a focal ratio of f/2.5 (nominal) was selected.

5.2. The Primary Mirror

The principle drivers for the primary mirror are the optical quality and cost. Secondary issues are the total weight, which will impact the telescope design, and the thermal capacity and time constant which will limit image quality under the best atmospheric conditions. The mirror styles considered were structured and solid.

5.2.1. Structured Mirrors

Structured mirrors are those having a substantial portion of the internal mirror mass removed leaving a sandwich made of a relatively thin faceplate and backplate separated by ribs. The backplate typically is pierced with holes and is sometimes omitted altogether. Owing to the reduced weight and thinner cross-sections, very short thermal time constants can be achieved, although forced air circulation in the mirror structure may be necessary. Several manufacturers can produce these mirrors.

Blanks assembled (fused together) from borosilicate glass plates and tubes are available from Hextek Corporation in Tucson with lightweighting up to 70-80%. Hextek can also produce cast mirrors similar to those made by the Steward Mirror Laboratory, but does not have spincasting facilities to form a curved front surface during the casting process. The sagittal region (2.5 cm deep for CHARA) would be cast filled with glass that would lengthen the cooldown and annealing period, and would then have to be machined out to form the reflecting surface.

Structured blanks are produced by Corning, Inc in Canton, NY by frit bonding fused silica or ULE* faceplates to rib structures assembled beforehand. All of the pieces in the assembly are cut from solid "boules" roughly 1.5 m diameter × 12 cm thick. ULE may also be flame welded (e.g., the HST primary). Structured blanks can be fabricated from Zerodur*, but the fusion processes are not generally used because the material will lose its "zeroexpansion" property if held at high temperature too long. More typically, Zerodur structures are machined which can also be done with ULE. A simple process of drilling out cores can be used, or more sophisticated methods can be used to machine out complex shapes. In the most advanced approach, slurry jets can be used to remove more than 90% of the mass.

Structured blanks from "exotic" materials (e.g., silicon carbide) were ruled out on the basis of limited confidence in availability or cost. Silicon carbide is also very difficult to polish.

5.2.2. Solid Mirrors

Solid blanks are expected to present the fewest design and support complications if the thermal effects can be managed satisfactorily. This requires selection of a blank material with a low coefficient of thermal expansion (CTE) and a suitably thin cross section in the blank.

Metal mirror blanks were ruled out because few suppliers are available and a satisfactory prototype test would almost certainly be required before committing to this mirror style for all of the telescopes. The classical option of solid borosilicate glass (Pyrex*) was not considered due to its relatively high CTE. ULE and Zerodur have CTE values near zero and are both available and widely used for 1-meter optics. An intermediate choice in terms of thermal expansion is fused silica (CTE about 17% that of Pyrex), however, high quality grades have little cost advantage over ULE. The material choice has been narrowed to ULE and Zerodur, the final choice to be governed by cost.

5.2.3. Selection of Blank Design

To satisfy the optical quality, thermal capacity and cost constraints, a study was undertaken to determine the thinnest mirror which would give adequate image quality with a completely passive support. An 18-point axial support was chosen because a relatively simple, passive, mechanical configuration is possible while providing better support than the 6 or 9 point supports commonly used in the past for relatively thick 1 m class mirrors. The lateral (radial) support chosen for its simplicity is a "central post" design which mounts in the central hole of the mirror and requires no other mechanism.

Plano-concave, concave-concave, and meniscus shapes were studied. Satisfactory optical performance was obtained with a plano-concave mirror 3.1 inches thick at the edge. (For additional details about the mirror figure, see the Technical Report No. 7, *Effect of Telescope Deformation on Visibility and Strehl*, available in this series.) The primary weight is approximately 300 pounds, roughly half that of typical existing solid 1 m telescope mirrors.

This mirror design and support chosen is felt to be near the simplest that might be expected to work for a 1-meter telescope of high optical quality. Also, we found from our parallel market survey that budgetary price estimates for structured blanks ranged from slightly higher to much higher than the cost of the solid blanks. The design of a mirror support for a solid blank was judged easier, cheaper than for a structured blank, and since the solid blank with passive support was found to give satisfactory performance the solid design was adopted and no further study of mirror design is planned.

6. THE MECHANICAL TELESCOPE MOUNTING

The two major mechanical assemblies are the azimuth mount and the tube comprising most of the telescope. Engineering layouts of both have been completed to a stage that allows initiation of finite-element structural analysis (FEA). The objectives of FEA are to ensure adequate stiffness of the structures while maintaining accurate optical positioning under varying gravity and thermal conditions. Some changes in structural configuration and element sizing are expected from FEA work now in progress. Thus, the following descriptions are still subject to change.

6.1. The Telescope Tube

The telescope tube will have semi-independent provisions for stiffness and thermal compensation. The stiffening structure will consist of three welded steel frames (primary mirror cell, elevation axis, and top end) connected by tubular steel trusses. This structure is not greatly different from most "Serrurier" style telescope truss systems. To maintain essentially constant primary-to-secondary spacing under varying thermal conditions, a second top end frame will be used to support the secondary and will be connected to the primary mirror cell frame by means of low-expansion (metering) tubes passing through the elevation axis and top end frames without significant axial restraint. The metering tubes will be laterally supported by the top end frame and axially supported by the primary mirror cell frame. The altitude axis frame will provide mid-height column stabilization. The gap between the two top end frames will be small (0.25 inches) to avoid bending of the low-expansion tubes. The connection between the top end frame of the stiff structure and the low-expansion tubes is currently under study. It may take the form of a closely fitted bushing with viscous fluid lubricant to act as a vibration damper or simply a mechanical flexure that allows axial movement of the tube while providing stiff lateral restraint.

6.1.1. The Primary Mirror Cell

The primary mirror cell will consist of a welded square frame of standard rectangular steel tube with cross-members to support the mechanisms connecting the structure to the mirror. The cross-members will support a circular post that extends upward through the central hole. The lateral support for the mirror will connect the mirror and the central post through flex elements designed to be axially compliant and laterally stiff. The axial support will consist of three whiffletree assemblies connected to the mirror through slender rods long enough to be laterally compliant while remaining axially stiff. ("Whiffletree" is a generic name for a mechanism with appropriate flexures to allow transfer of axial support from one support point to multiple points without imposing non-axial forces.) Small metal pads will be bonded to the mirror for this purpose. Each whiffletree will be a lever, pivoted at its center on one of the cell crossmembers, with a three-arm tripod on each end. A swivel joint within each tripod will allow it align to the rear mirror surface. The mirror cell is shown in Figure 2.

Since it may be desired to precool the mirror to slightly below the expected nighttime temperature, the mirror cell is partially enclosed and sealed to allow forced circulation of conditioned air around the mirror.

For installation, the mirror will be installed in the cell away from the telescope and the cell then mounted to the telescope tube. For removal the process will be done in reverse.

6.1.2. The Secondary Mirror Assembly

The secondary top end frame will form a square with vanes extending inward from each corner to support a central tube for mounting the secondary. Each corner of the frame will be connected to low-expansion metering tubes as described earlier. The frame can be relatively massive as there is a need to locate sufficient mass at the top end of the telescope to balance the primary. Each of the four vane sets will include an upper and lower vane

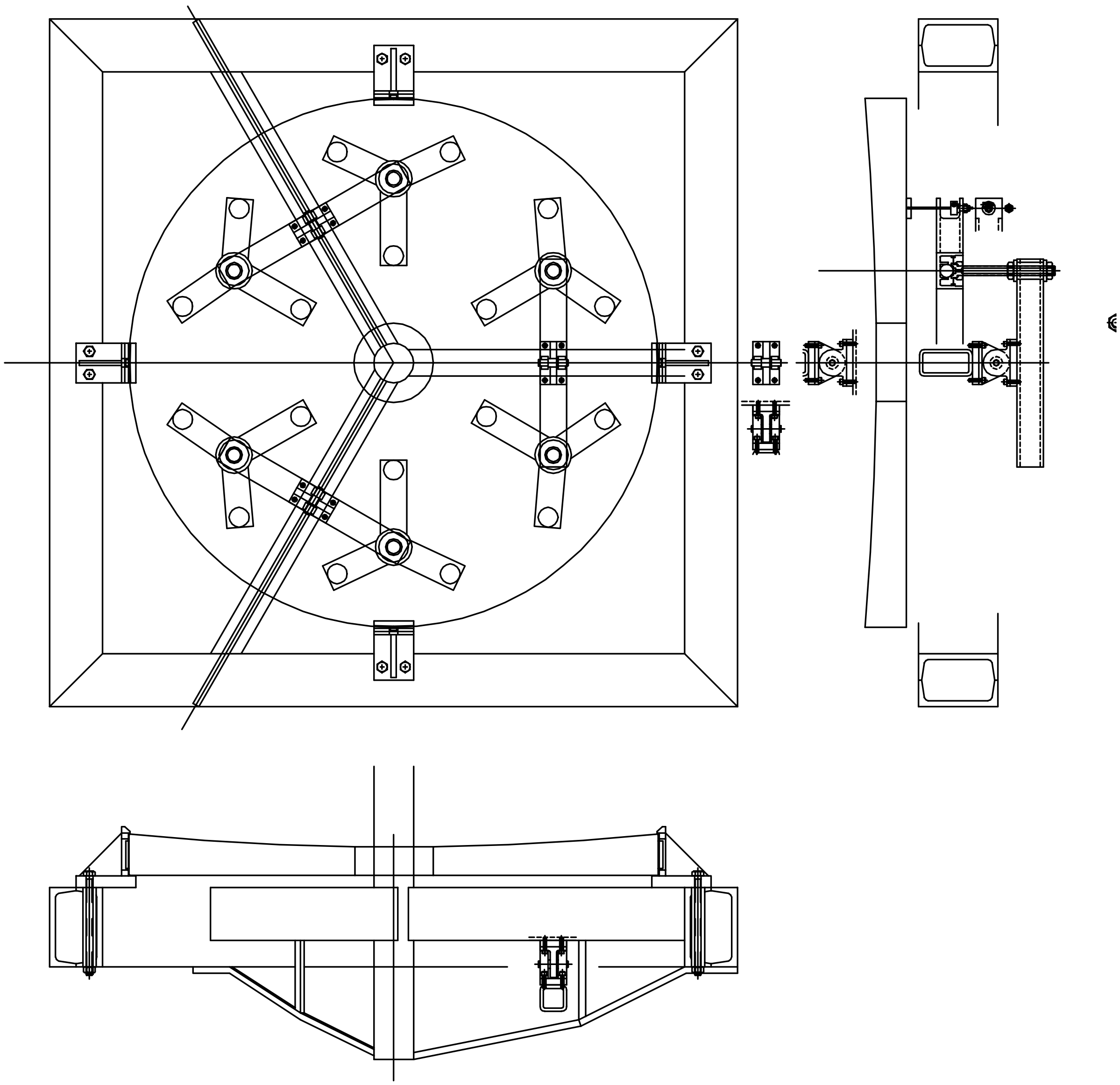

FIGURE 2. Mirror cell.

having different cross-sections. The cross-sections will be adjusted, based on FEA, to allow a tilt of the secondary to keep it correctly aligned to the primary under varying telescope elevation. The secondary mirror assembly is shown in Figure 3.

A focusing drive will be provided and a driven mirror tilt provision is currently under consideration.

6.1.3. The Tertiary Mirror Assembly

The tertiary mirror at the elevation axis deflects the parallel optical beam to the azimuth axis. This mirror is supported on the upper end of the central tube (post) passing through the hole in the primary mirror. The tube is also supported laterally near the tertiary mirror with vanes (in the shadow of the secondary vanes). The tertiary assembly and its tube support will decouple from the primary center post and remain in the telescope when the primary and cell are removed. Adjustment of the mirror tilt will be done manually at assembly. No driven adjustments are planned. The tertiary assembly is shown in Figure 4.

6.2. Vignetting

The telescope will have a blank diameter of 40 inches (giving a nominal clear aperture of 1-meter). The primary will have a central hole diameter of 5 inches. At f/8 the secondary will have a required diameter of 5 inches, and will be very slightly oversize. All secondary and tertiary support structure (except the vanes of course) will be hidden behind the secondary obscuration.

6.3. The Azimuth Structure

The 5-mirror optical coudé design leads naturally to an asymmetric "outboard" style azimuth yoke which is advantageous for rigidity. The lowest frequency resonance of a yoke with equal arms is almost always the tuning fork mode. Since the stiffness of a circular tube member increases as r^4, while the weight no faster than r^2, it is advantageous to increase the size of one arm of the yoke and use it to strengthen the structure.

The azimuth mount will consist of a stationary 30-inch diameter tube surrounded by a coaxial rotating 36-inch diameter tube that will form one arm of the yoke. (Standard pipe dimensions are specified.) A 30-inch diameter tube will be welded to the 36-inch tube extending horizontally to support a smaller (6-in $\times$ 12-in) rectangular tube that forms the outboard yoke arm. The outboard yoke arm will be somewhat compliant along the altitude axis while retaining high stiffness normal to the altitude axis. The outboard yoke arm will support one altitude axis bearing (a spherical roller pillow block style) while the larger arm will support a pair of angular contact bearings capable of withstanding radial and thrust loads. Thus, the altitude axis frame will be strongly coupled to the larger yoke arm which provides greater rigidity than would occur if both yoke arms were equally sized at a smaller diameter.

The space between the 30-inch stationary and 36-inch rotating tubes can be used for mounting a pair of nested cylinders, one attached to each tube. Together, these cylinders comprise an azimuth axis motion damper when a viscous fluid is filled into the annular cup formed by one of the cylinders. Details of this provision are still under study.

Additional detail of the azimuth structure is shown in Figure 5.

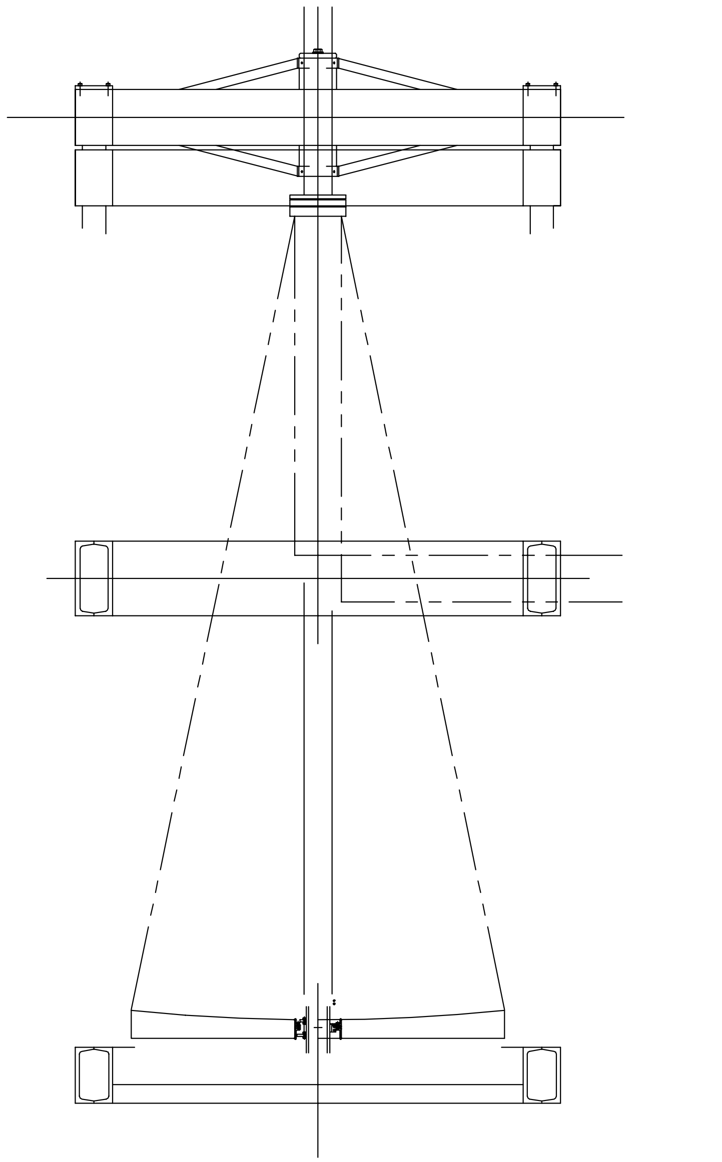

FIGURE 3. Secondary assembly.

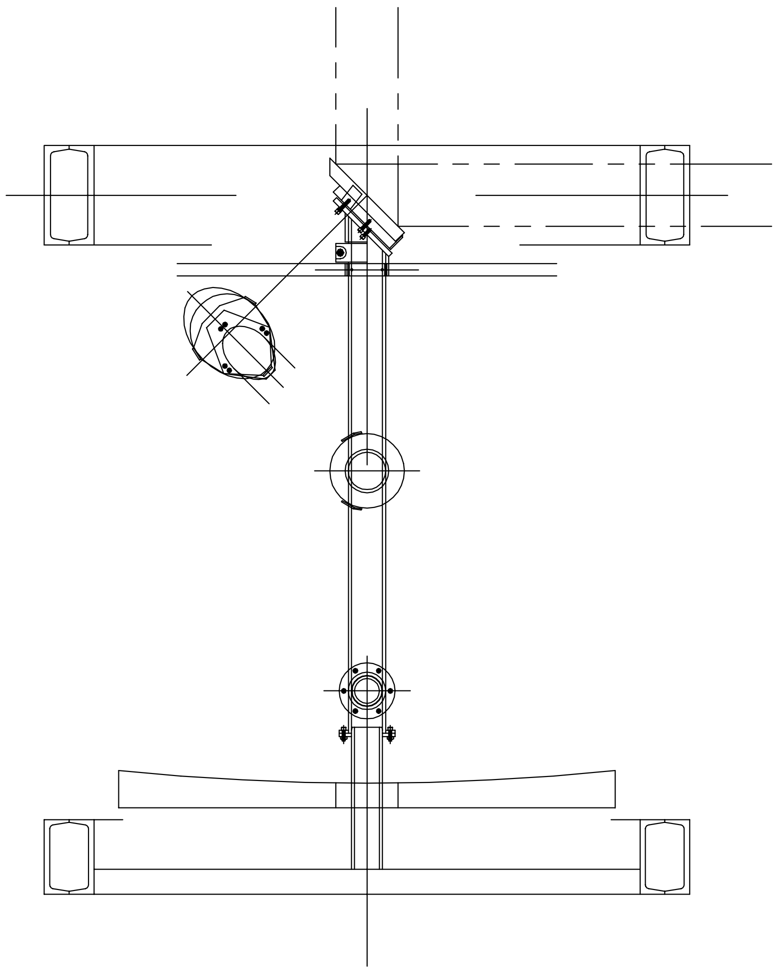

FIGURE 4. The tertiary mirror assembly.

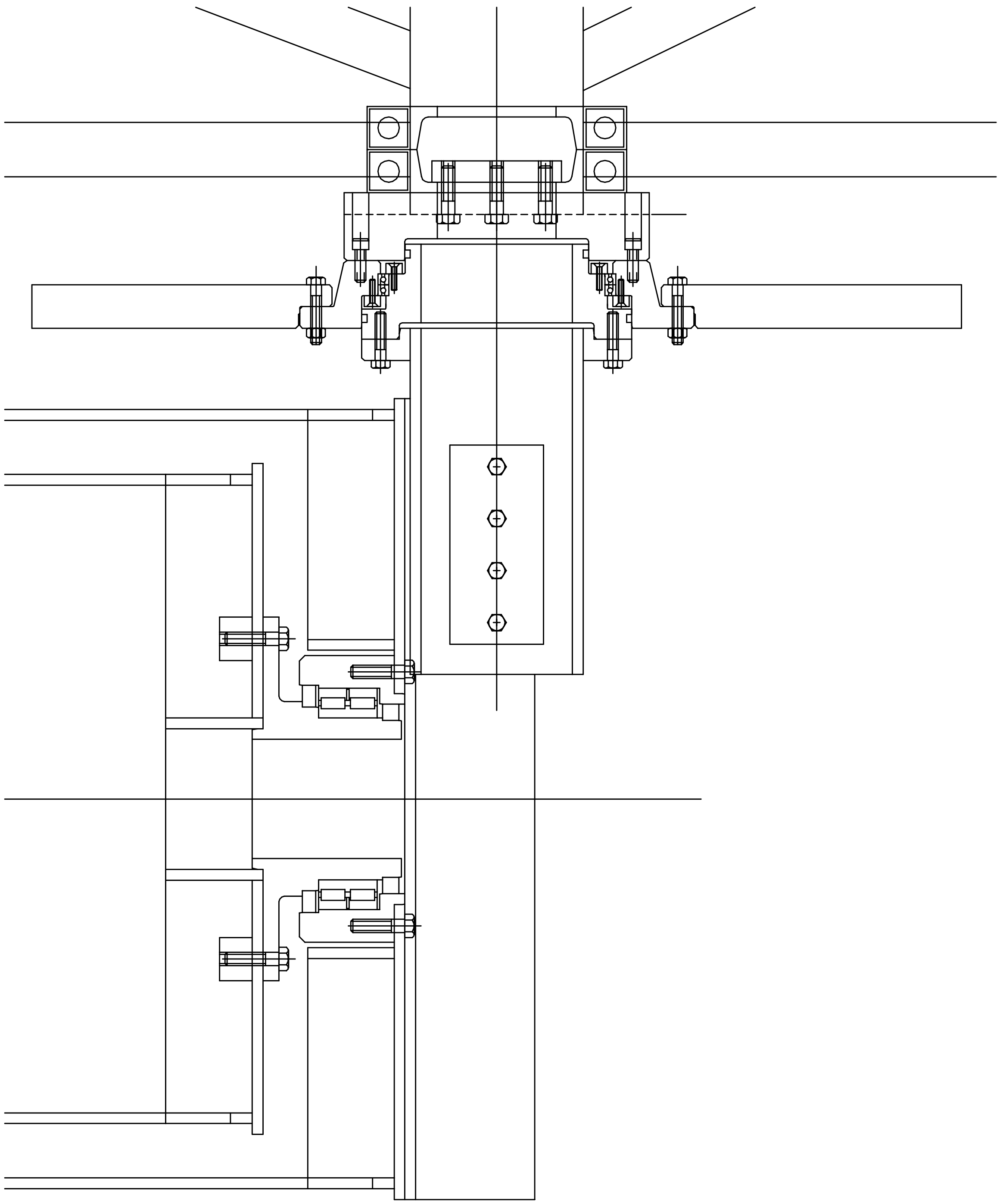

FIGURE 5. Azimuth and elevation bearings.

6.3.1. The Azimuth Bearings and Cable Wrap Provisions

The azimuth bearings consist of a large diameter ball bearing at the base of the rotating 36-inch diameter tube and a smaller cylindrical roller bearing atop the 30-inch diameter tube. The ball bearing will withstand radial and vertical load (the weight of the rotating structure) while the roller bearing will only resist radial loads. At assembly, the bearing runouts will be measured and aligned to minimize the pointing error that would otherwise occur. This will allow "standard accuracy" bearings to be used.

The light beam will pass through the upper bearing bore down through the interior space in the stationary 30-inch tube. It will be possible to surround the beam with a smaller diameter tube (e.g., 6-inch diameter) that conceivably could support the entrance window to the evacuated pipes leading to the central laboratory. The space between the smaller tube and the 30-inch tube will be used for loosely draped cables. The cables will pass through a 1-inch wide annular space just outside the light beam space and inside the upper bearing bore which will be sized for this purpose. Cables will be draped to allow approximately $+270^o$ of azimuth rotation. Only a few cables should be required for the drives and focus control.

6.4. Drive System and Control Software

The drives have not yet been designed although work may begin in February 1995 if resources remain in the NOAO contract. Otherwise they may be a TBD in the bid package. It is tentatively planned to use friction roller drives on both axes with some form of controllable DC motor. Commercial options will be explored. Locations of the drive journals are shown in Figure 1. The azimuth drive motor may be mounted either on the stationary pier plate, suitably extended, or on the lower side of the horizontal 30-inch diameter yoke arm connector tube. In the latter case, the azimuth journal would be stationary. The altitude axis drive will be mounted on a bracket attached to the side of the rotating 36-inch diameter yoke arm. For either axis, it will be necessary to choose the motor size and style before mounting hardware can be properly designed.