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Design and fabrication of a compact lidar telescope

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ABSTRACT

A prototype compact off-axis reflective lidar telescope has been designed and fabricated for remote sensing of atmospheric winds from space and airborne platforms. The 250 mm aperture telescope consists of two mirrors and a collimating lens to achieve a very compact size, without any central obscuration. It has no internal focal point to prevent air breakdown, and the pupil relay optics has also been eliminated. This paper presents the results of optical design and sensitivity analysis along with the predicted performance. The major design issues for lidar systems, particularly the one that utilizes coherent detection for higher sensitivity and Doppler frequency extraction, are the wavefront quality, polarization purity, and a minimum backscattering off the reflective surfaces. These design issues along with the other optical characteristics of this lidar telescope are presented. The effect on the wavefront quality of the tilt, decentration and axial spacing tolerances for the mirrors, collimating lens and quarter wave plate is discussed.

The important optomechanical design features include high rigidity, long term stability and a low fabrication cost. The mirrors are directly bolted and pinned to the support structure to achieve the required alignment accuracies and long term stability. The mirrors and structure are made from aluminum for low cost, and to minimize the adverse effects of differential thermal expansion. The aluminum mirrors are stress relieved and electroless nickel plated prior to single-point diamond machining. The mirrors are also post-polished to achieve a very low surface roughness to minimize the backscattering.

Key words: Lidar telescope, off-axis reflective optics, tolerance analysis, metal mirrors, diamond machining

1. INTRODUCTION

Recent advances in diode-pumped solid lasers have provided the new possibilities for the development of robust, compact and efficient coherent lidars [1]. However, space and airborne applications of coherent lidars continue to demand for more compact and robust designs with a higher degree of sensitivity [2,3]. For a space-based coherent lidar, the telescope and scanner along with their associated support structures and control units account for most of the weight and size budget of the system. Therefore, any reduction in their mass will have a major impact on the mission cost. This paper describes the design, performance and fabrication technique of a 250 mm telescope that can significantly reduce the size and weight of a space-based coherent lidar operating at 2 microns wavelength. The telescope design as described here can be readily scaled to 500 mm aperture diameter with similar alignment and fabrication tolerances [3]. Even though this lidar telescope has been designed and fabricated based on requirements of a space-based instrument, it can directly benefit many airborne applications of coherent lidars.

2. OPTICAL DESIGN

The overall function of the coherent lidar optical system is to expand the laser beam, and direct it towards the atmosphere in a conical scan, to receive the back scattered radiation, and compensate for the wavefront and boresight errors caused by the scanner and spacecraft/aircraft motions. The major lidar system requirements are: (1) beam expanding aperture of 250mm; (2) input laser beam diameter of 10 mm; (3) conical scan rate of 10 RPM; (4) nadir angle of 30 degrees; (5) no internal focal point to avoid air break down in ground system testing; (6) diffraction limited beam quality; (7) lag angle compensation to maintain the boresight to within 1 micro-radian.

The beam expanding telescope is an off-axis catadioptric system, which serves both as the transmitter laser beam expander and as the receiver collecting telescope. Various configurations for the telescope were evaluated against the performance requirements. An off-axis configuration has been selected to eliminate the central obscuration of an on-axis design, which degrades the beam quality due to the diffraction pattern of the obscuration. The off-axis configuration also effectively reduces the back scattering of the transmitted pulses by the front surface of the telescope secondary mirror. A Galilean type of telescope has been employed to eliminate the real focus of the Keplierian type of telescope. The beam wander problem of a Galilean telescope (because of no real exit pupil) can be solved by using additional corrective optics. A catadioptric design with a refractive exit lens has been used to provide enough back-relief space to accommodate the beamsplitter, derotator and lag angle compensator. Figure 1 is the optical layout of this compact two-mirror and one lens off-axis telescope.

The two mirror are a parabola and a hyperbola as in a standard Cassegrain type of telescope. An aspheric negative lens been used to recollimate the beam. Zinc Sulfide has been selected for the re-recollimating lens to facilitate the integration and alignment of telescope using visible HeNe laser. The designed telescope has: (1) a field of view of 0.17 degree to cover the lag angle of the return beam; (2) afocal magnification of 25X to expand the 10 mm beam to a 250 mm diameter; (3) RMS wavefront error of 1/10 wave at the exit pupil for 2.067 micron wavelength; (4) zero obscuration and vignetting; (5) no internal real focus; and (6) two mirrors axial spacing of only 175 mm. Figure 2 shows the wavefront error of this telescope for the transmitted and return beams, and Figure 3 shows the point spread function in the telescope exit space for both the beams.

3. TOLERANCE ANALYSIS

It is easy to design an optical system that can never be built because of its parametric sensitivity, i.e. very tight fabrication and assembly tolerances. Parametric sensitivity of the telescope has been analyzed to determine its performance for real fabrication and assembly tolerances. The details of wavefront error and boresight sensitivity analysis for the two mirrors and collimator lens are given in Reference 3 with the wavefront error for the ideal telescope, zero allowance for fabrication and assembly tolerance, is $\lambda/200$ P-V. Table 2 lists the boresight errors induced due to all these tolerances. The most sensitive element is the primary mirror. To maintain 1/10 λ RMS wavefront and a one micro-radians boresight system performance, the decenters should be less then 0.01 mm, and the tilts should be less than 0.017 milli-radians.

4. OPTOMECHANICAL DESIGN

A simple approach was used for the optomechanical design of the prototype telescope to minimize the fabrication cost and time. The telescope consists of a box-type support structure, a primary and a secondary mirror, and a quarter-wave plate and a collimating lens as shown in Figure 3. The primary mirror is designed to machining because of their off-axis aspherical configuration, and the large size of the primary mirror. A brief description of some of the important design features of the two mirrors and the support structure is given in the following sections.

4.1 Design of mirrors

The primary mirror has a clear aperture diameter of 250 mm and its mechanical axis is offset 187.5 mm from the optical axis. The diameter of primary mirror is 270 mm to provide an extra 10 mm margin around the edges to account for the edge roll-off and other polishing and machining errors. The back of the mirror is designed to be orthogonal to the optical axis to simplify the design of the diamond machining fixture. This design approach results in a mirror of non-uniform thickness, the top edge being much thicker than the edge closest to the optical axis. Although this non-uniform thickness of the mirror compromises its thermal performance, it results in substantial cost savings in the fabrication of the mirror blank and the diamond machining fixture.

The mirror is mounted to the support structure by using three screws and two dowel pins located on a common bolt circle of 200 mm diameter. The three 0.25-20 screws are equally spaced 120° apart, while the two 6.35 mm (0.25") diameter dowel pins are located 180° apart from each other as shown in Figure 4. The threaded holes for the screws and a precision hole and a slot for the two pins are machined into the back surface of the mirror. Three small raised pads are provided around the threaded holes for a semi-kinematic mounting of the mirror to the structure and the machining fixture to minimize mirror distortion. The front of the primary mirror substrate is made spherical to a best fit radius of 555 mm to facilitate its rough machining. A small flat surface is also provided at the top outer edge for alignment and machining reference purposes.

The secondary mirror is relatively much smaller in size (60 mm diameter), with an offset of only 30 mm between its mechanical axis and the telescope optical axis. The back surface of this mirror is also designed to be orthogonal to the optical axis to simplify the design of its diamond machining fixture. Since the secondary mirror is much thinner than the primary mirror, a flange is provided for its mounting features as depicted in Figure 5. This flange could not be made full round because of the space constraints, thereby resulting in a slightly modified spacing between the screws. In this case, four screws have been provided for adequate mounting instead of the three screws normally used in kinematic mounting designs. The precision hole and slot for the two dowel pins are located 180° apart on the same bolt circle as the screws. The front surface of the secondary mirror substrate was made flat and tapered to minimize the fabrication cost.

4.2 Design of diamond machining fixtures

Since the back surfaces of both mirrors are normal to the optical axis, the design of their diamond machining fixtures is fairly simple and straight forward. Both fixtures basically consist of flat circular plates with appropriate mounting features for the mirrors. These fixtures are designed to support and diamond machine two mirrors each simultaneously to minimize the imbalance problems due to centrifugal forces during machining.

The diamond machining fixture for the primary mirror consists of two circular plates, 660 mm in diameter and 25 and 50 mm thick as shown in Figure 6. A two-piece fixture design is needed in this case because of the back-mounting configuration of the primary mirror and the design of the chuck of diamond machine. The 50 mm thick plate is designed to mount to the chuck directly using six 0.625-13 screws located on 356 mm (14") diameter bolt circle. The 25 mm thick plate has two 6.35 mm (0.25") diameter dowel pins and three counter-bored clearance holes for 0.25-20 screws on 200 mm diameter bolt circles, whose centers are located 187.5 mm (offset distance) from the center (spin axis) of the plate. The two mirrors are bolted to this plate first, and then this 25 mm thick plate is designed to be bolted to the other 50 mm thick plate.

The diamond machining fixture for the secondary mirror is a simple 140 mm diameter x 19 mm thick circular plate as illustrated in Figure 7. It is also designed to support two mirrors simultaneously for machining. This fixture has two dowel pins and four 6-32 threaded holes on a common bolt circle for each mirror. The centers of these bolt circles are located at 30 mm (offset distance) from the center (spin axis) of the plate.

4.3 Design of support structure

A box-type structure has been designed to support the two mirrors and other components of the telescope as depicted in Figure 8. This design configuration was selected to minimize the weight and cost of fabrication. The support structure consists of a front and a back plate, which are connected by a top and a bottom plate, plus six gussets (three on each side). All these ten 0.25" thick plates can be machined individually, and then bolted and pinned together to produce a very rigid and lightweight support structure. Raised areas have been provided on the front and back plates for mounting the two mirrors. Extra material is provided on the raised areas so that these mounting surfaces can be machined flat and parallel to each other from the same side in the assembled box to obtain the correct axial spacing between the two mirrors.

The front plate has four 6-32 threaded holes and two 3 mm (0.125") diameter dowel pins for securely mounting the secondary mirror. The back plate has three clearance holes for the 0.25-20 screws and two 6.35 mm (0.25") diameter dowel pins for mounting the primary mirror. Mounting features have also been provided in the bottom plate to install the quarter-wave plate and collimating lens linear translation stage. A number of additional threaded holes are provided in different plates of the structure to install other components of the lidar system such as the wedge scanner, derotator and beamsplitter.

4.4 Design of quarter-wave plate and collimating lens mounts

Since the alignment tolerances for the quarter-wave plate and collimating lens are quite loose, simple bonded type mounts have been designed for these two optical elements as depicted in Figure 9. This bonded design not only simplifies the design of the mounts resulting in low fabrication cost, it also minimizes the thermally induced stresses in the optics due to differential expansion as a result of changes in the ambient temperature. The 25 mm diameter x 1 mm thick quartz quarter-wave plate is directly bonded into an L-shaped aluminum bracket using an appropriate RTV. As the axial spacing and decentration of this flat optical element are not critical, only two screws are used for securing its mount to the structure.

The collimating lens mount is similar in design, but it is designed to mount to a linear translation stage for varying the focal length of the telescope from 100 meters to infinity. Although only a small off-axis part of the aspherical lens is needed, a complete 37 mm diameter circular lens, which is centered on the optical axis, is used. This configuration simplifies the mounting design and fabrication of the lens. The Cleartran (ZnS) lens is directly bonded into its aluminum mount using RTV.

5. FABRICATION OF MIRRORS

As the support structure, mirrors and other optical mounts are all made from 6061-T6 aluminum alloy, these components can be machined using standard tooling and methods for precision optical applications. All these parts were rough machined and then stress-relieved prior to finish machining of the critical mounting features.

A brief description of the fabrication procedures employed for the two mirrors and their diamond machining fixtures is given as follows.

5.1 Fabrication of diamond machining fixtures

The surface figure of the finished mirrors directly depends on the quality of the fixtures used for their diamond machining. Therefore, it is very critical to achieve best possible flatness on these fixtures to prevent distortion of the mirrors when mounted to these fixtures during diamond machining. After rough machining and stress relieving, the 50 mm thick primary mirror fixture plate was mounted on the chuck of Moore diamond turning machine. The outer diameter and front surface of this plate were then diamond machined to obtain a highly flat surface. The 25 mm thick fixture plate was then bolted to the 50 mm thick plate and its front surface was diamond machined. This plate was then removed, turned over and then rebolted to the 50 mm thick plate to diamond machine the other side of the plate. This diamond machining of all mating surfaces of the fixture plates eliminated the possibility of any warping when the plates and mirrors are rigidly bolted to each other.

5.2 Fabrication of mirrors

The rough machined mirrors were thermally cycled to enhance their long term stability prior to diamond machining. The mirrors were placed in a boiling water bath for 5 minutes, then removed and brought to the room temperature. Next, they were held above the liquid nitrogen (LN_2) surface in a container for a few minutes and then submerged in it until the LN_2 stopped boiling. Next, they were again put into the boiling water for one minute. This thermal cycle was repeated three times. Then, the three pads on the back side of primary mirrors were lapped flat and coplanar before installing the two mirrors on the 25 mm thick plate. This plate was then bolted to the 50 mm plate already installed on the chuck of the diamond turning machine. The mirrors were then diamond machined to the required aspherical shape using a single point tool. These mirrors were then plated with a thin layer (125 - 150 microns thick) of electroless nickel (11% phosphor by weight) before finish diamond machining them again.

A similar procedure was followed for fabricating the secondary mirrors. This included thermal cycling the mirrors, lapping the back surfaces, then diamond machining the desired aspherical surface in bare aluminum. The mirrors were then electroless nickel plated, and finally finish diamond machined.

The surface roughness obtained on these mirrors after diamond machining was of the order of 200-300 Å on the primary mirrors and 50 Å on the secondary mirrors. This level of surface roughness is deemed too high for lidar applications because it can produce excessive scattering and back reflection especially from the secondary mirror. Therefore, both the primary and secondary mirrors were post polished using diamond paste and aluminum oxide. A surface roughness of better than 15Å and 50 Å was obtained on the secondary and primary mirrors respectively after polishing. The figure error of both mirrors was controlled to one wave peak-valley at HeNe wavelength. Then, the two mirrors were coated with gold and a protective material for high reflectivity and durability.

6. CONCLUSIONS

The optical design and sensitivity analysis of a compact off-axis prototype telescope for space-based lidar applications has been presented. The optomechanical design emphasizes the low cost and lightweight by using aluminum for the two mirrors and other structural parts. A very stable and rugged telescope has been designed by using simple designs and standard precision machining methods. The two mirrors are rigidly bolted to a lightweight box-type of structure, requiring no alignment at assembly. The next phase of work will involve assembly and integration and testing of the telescope. The telescope performance will be then demonstrated in a coherent lidar system along with the other optical subsystems and components including the scanner and the signal beam derotator. This work was supported by the Electro-Optics Branch of NASA Marshall Space Flight Center.

7. REFERENCES

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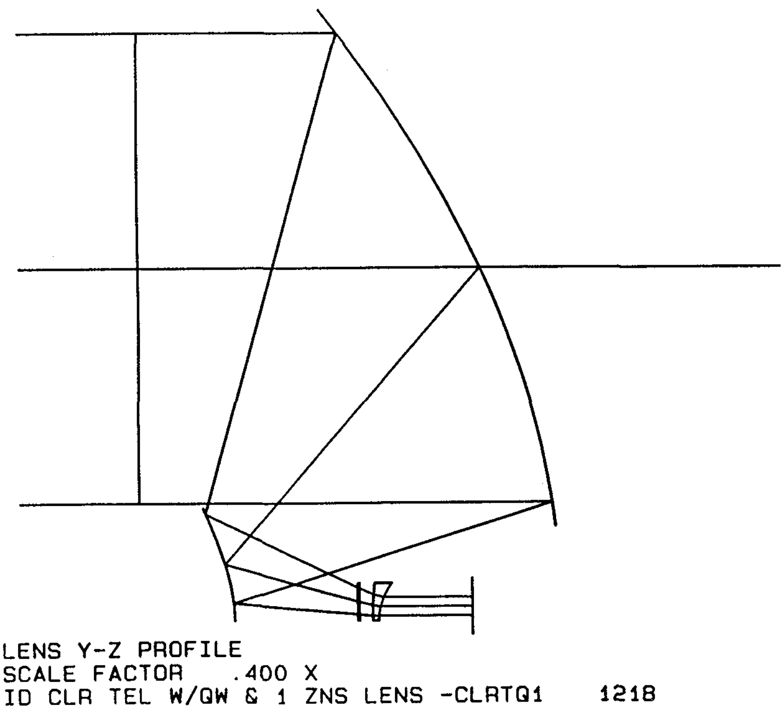

Figure 1. Optical layout of the telescope showing configuration of major optical elements.

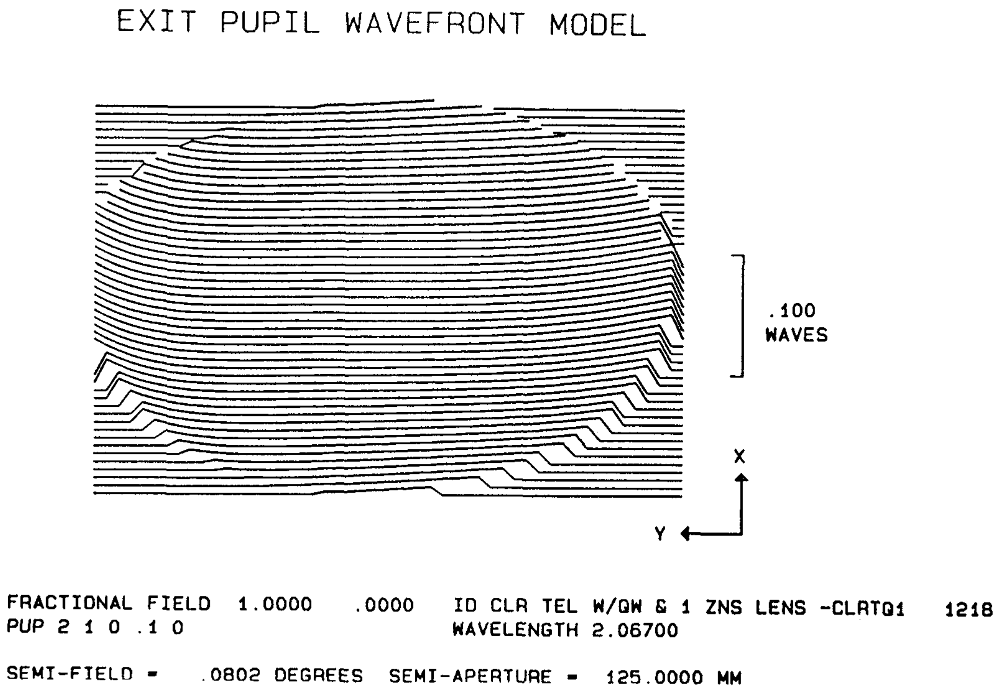

Figure 2(a). Wavefront error in telescope exit space.

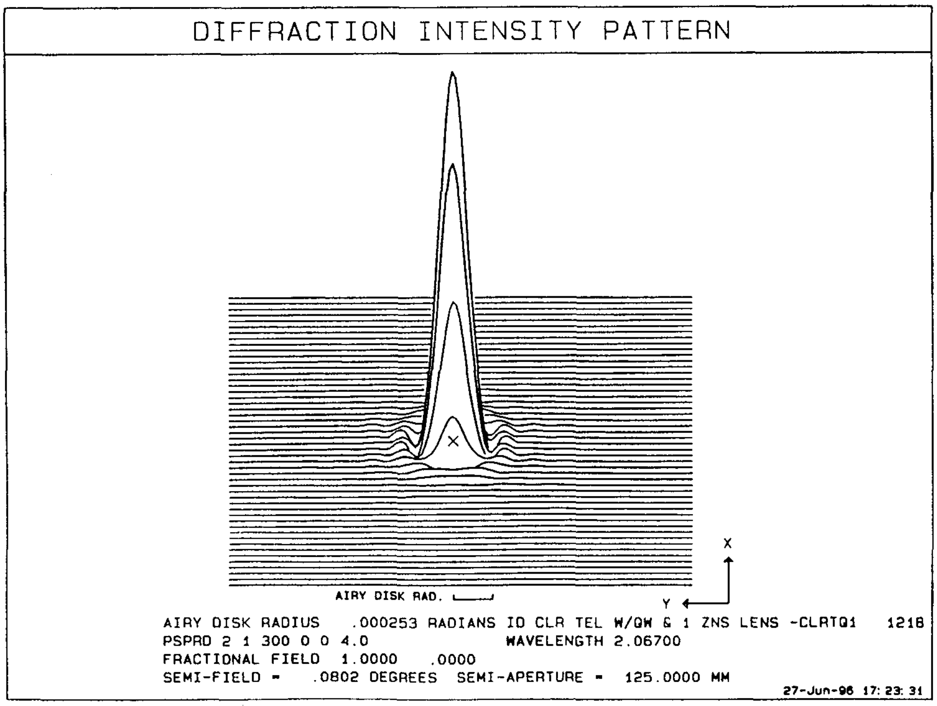

Figure 2(b). Point spread function in the exit space.

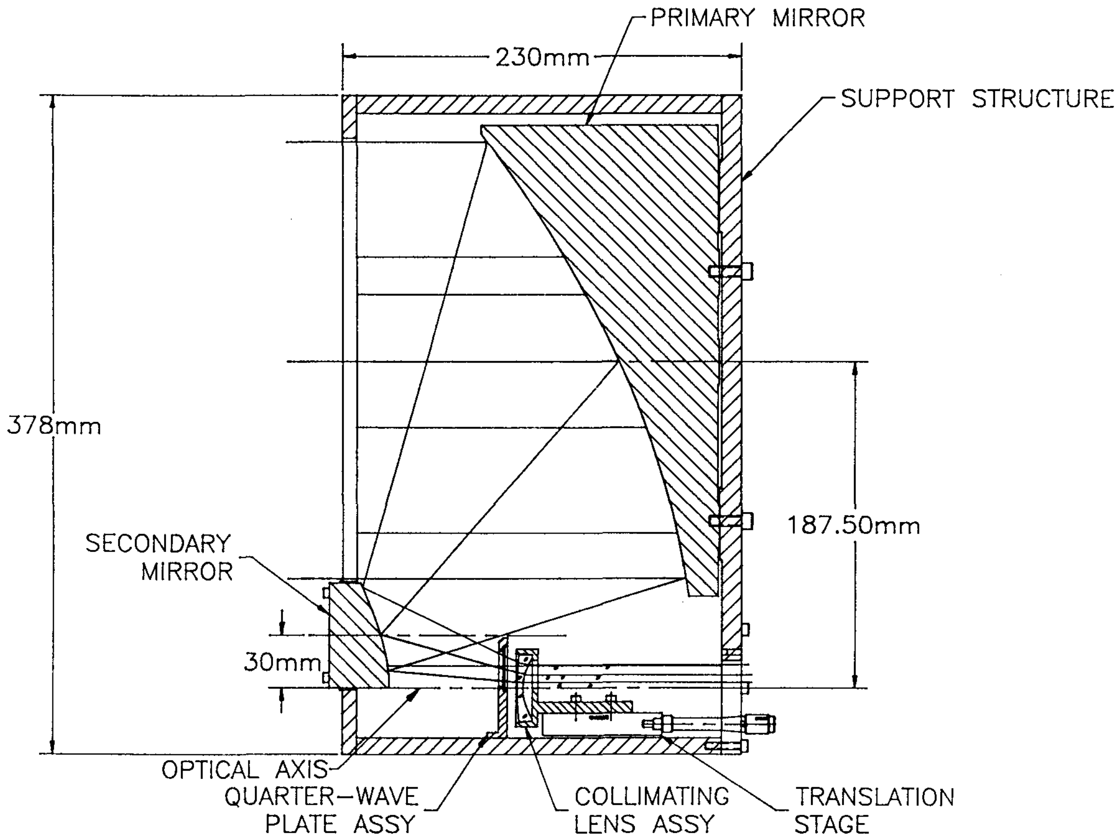

Figure 3. The telescope assembly showing major optical and structural parts.

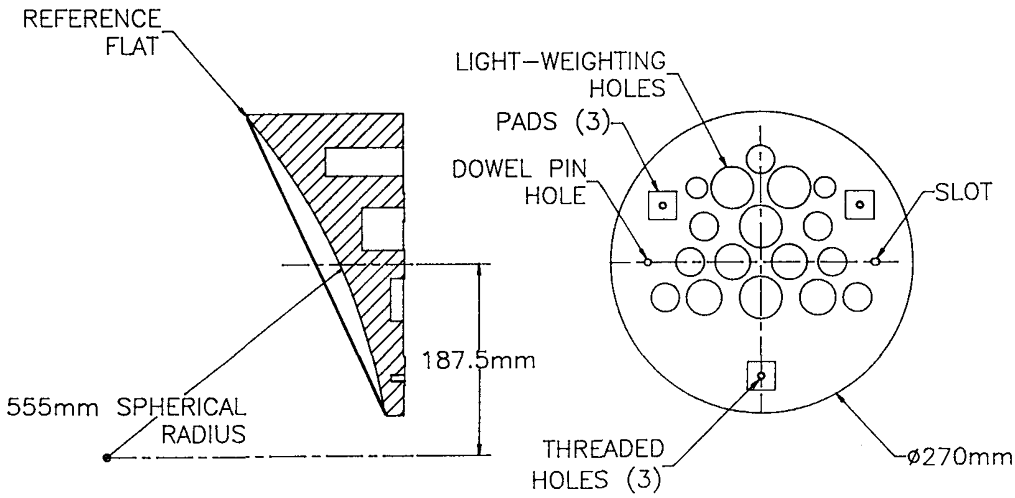

Figure 4. The mounting features and light weighting scheme for the primary mirror.

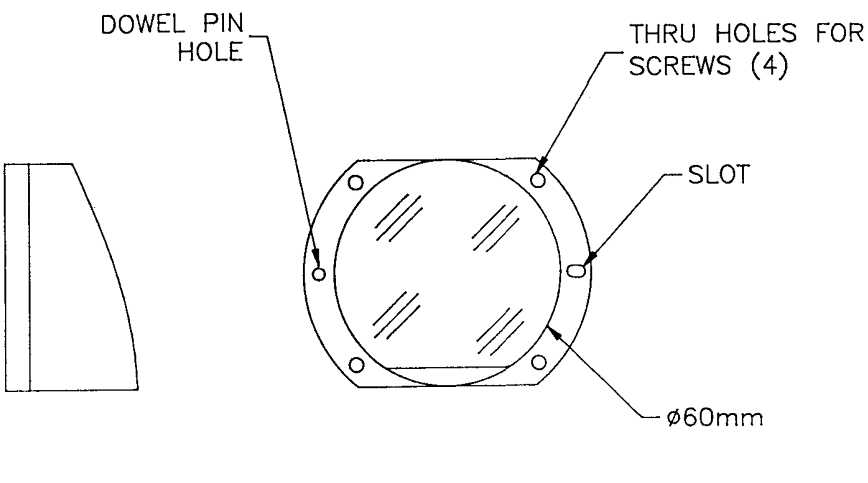

Figure 5. The mechanical design features of the secondary mirror.

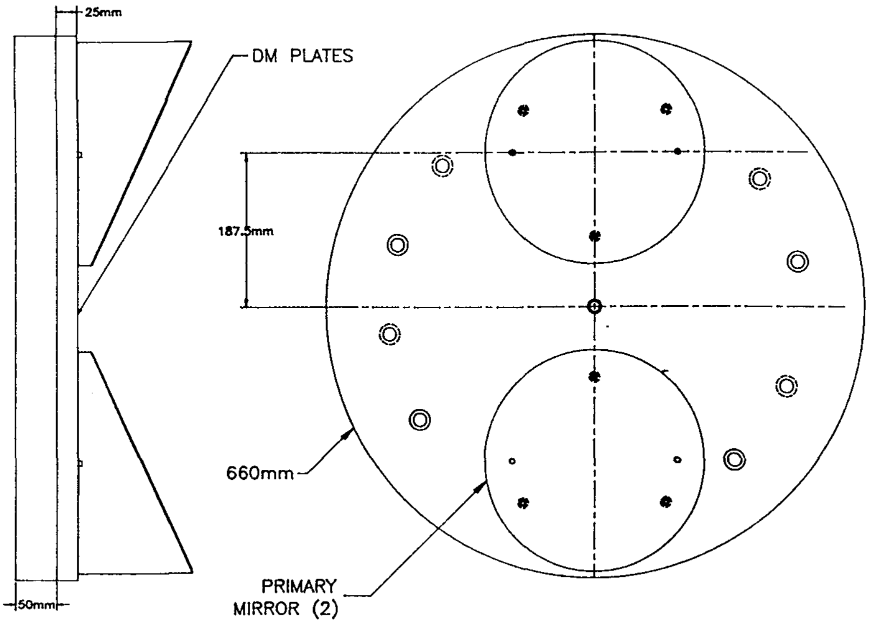

Figure 6. The primary mirror diamond machining fixture

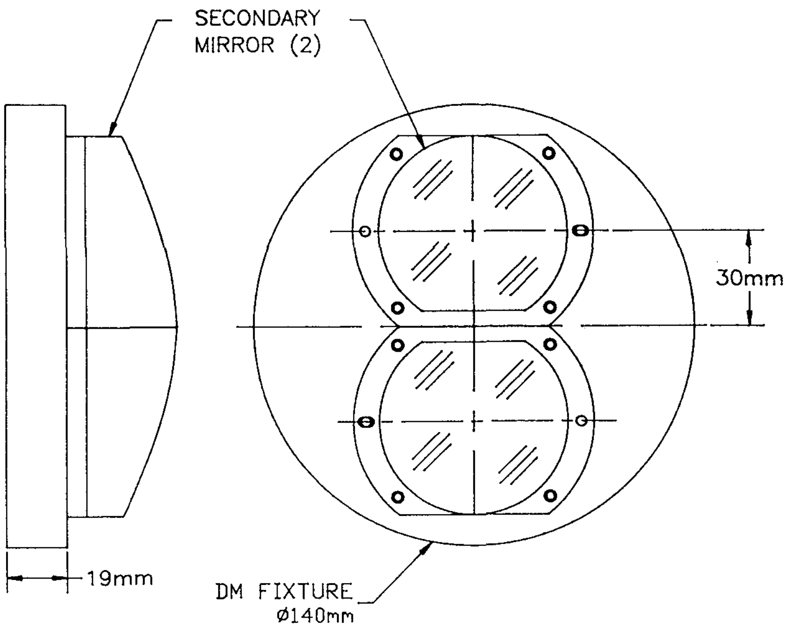

Figure 7. The secondary mirror diamond machining fixture.

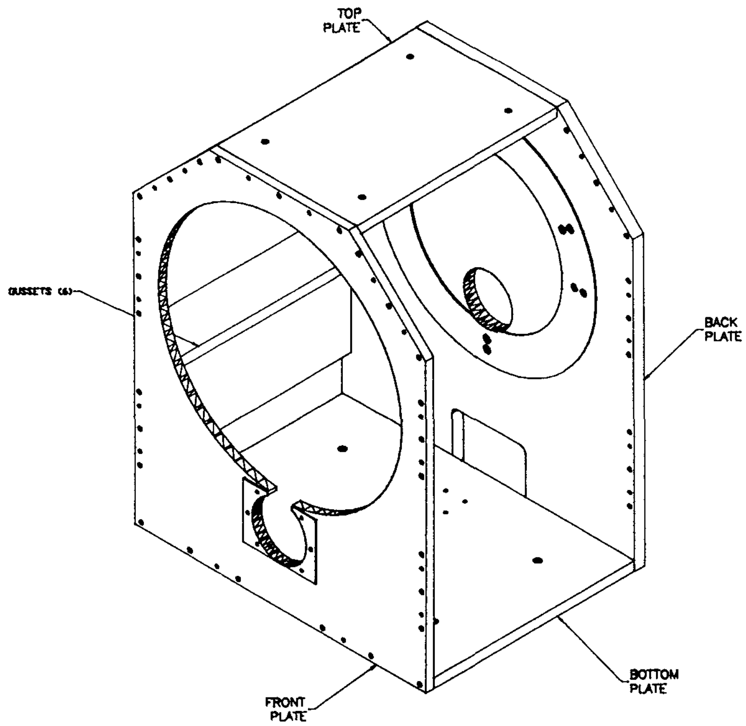

Figure 8. The telescope support structure showing bolted and pinned construction.

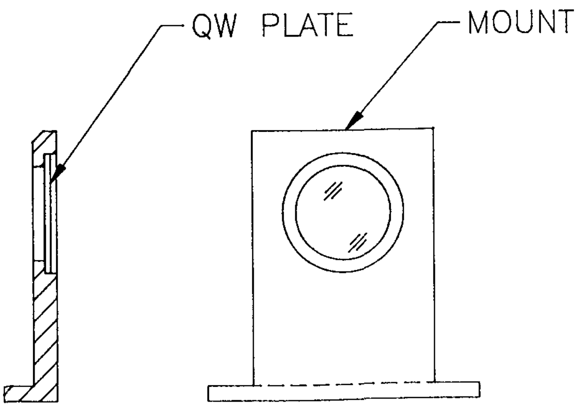

Figure 9(a). The bonded type optical mount for quarter-wave plate.

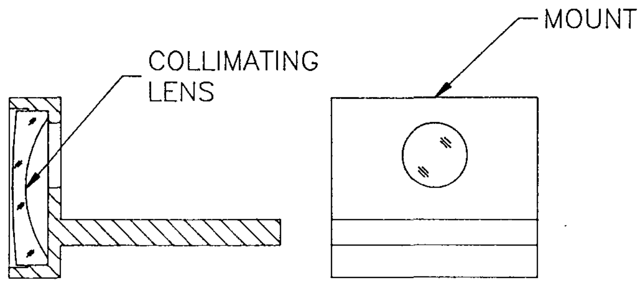

Figure 9(b). The bonded type optical mounts for collimating lens.