Design and fabrication of a large primary reflector structure for space laser power beaming

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ABSTRACT

This paper discusses the design issues and fabrication considerations specifically related to a large twelve meter, graphit c-epoxy space truss that has been developed to provide support of the primary mirror system for the SpacE Laser ENErgy (SELENE) Beam Transmission Optical System (BTOS). Details of the optical system and wavefront corrector concepts have been discussed in prior papers. Specific issues which are addressed in this paper include optical performance needs, environmental requirements, and low-cost fabrication techniques.

2. INTRODUCTION

BTOS is a portion of a larger project entitled SpacE Last.r Electric ENErgy (SELENE). The SELENE project is managed by Marshall Space Flight Center and utilizes a high energy, free electron laser to transfer energy from the ground to orbiting spacecraft or other targets such as a lunar colony. BTOS is the system that transmits the beam energy from the laser to the target. BTOS receives a one mete.r diameter energy beam which has been cleaned up so that the Strehl ratio is 0.9 or greater,

To satisfy requirements for the SELENE missions, which include a Strehl ratio greater than 0.5, it is necessary for the beam to correct for atmospheric disturbances.[1] Atmospheric correction for the BTOS project is accomplished through the usage of an active primary mirror. To achieve the necessary correction, the initial design for the primary mirror system requires the usage of over 150,000 hexagonal, 3 cm flat-to-flat mirror segments, each of which arc capable of being commanded at over 300 hz in tip, tilt, and piston by utilizing three voice coil actuators.[2]

Due to the challenging control requirements, the project felt it was necessary to determine if dynamic interaction between the control system and the mirror segments, mirror support panels, and primary mirror support structure would be a problem early in the program. Once evaluated, efforts can be concentrated to correct for any disclosed problems. The effects of dynamic interaction can be simulated in computer models when all the structural components arc characterized to the same level of fidelity. Unfortunately, the spatial scales involved in BTOS run the gamut from 3 cm sizes operating at 300+ cycles per second to 1200 cm sizes vibrating at 5- 10 cycles per second. It was decided that a testing program be developed that would answer the questions related to dynamic interaction.[3] One portion of that test program involve.d dynamic testing of a selected number of mirror support panels mounted to a full size primary mirror support structure, It was felt that a prototype structure 12 meters in size must be made along with representative mirror segments and mirror support panels, in order to determine whether or not dynamic interaction problems would exist.

Design issues for the hexagonal, twelve meter flat-to-flat, graphite-epoxy primary mirror support structure focus on deflection requirements caused by gravity and thermal conditions, the avoidance of dynamic interaction with the actuated mirror segments, and producing tight, non-slip joints. Fabrication considerations focus on low procure.ment cost, minimizing labor intensive steps, and minimal assembly time.

3. DESIGN ISSUES

The. design for the entire BTOS structure. must consider many issues. Concerns related to performance of the optical system have priority over all other concerns. Strength issues are important as well because BTOS is integrated and operate.d in the presence of environmental conditions such as gravity, thermal gradients, and atmospheric turbulence.

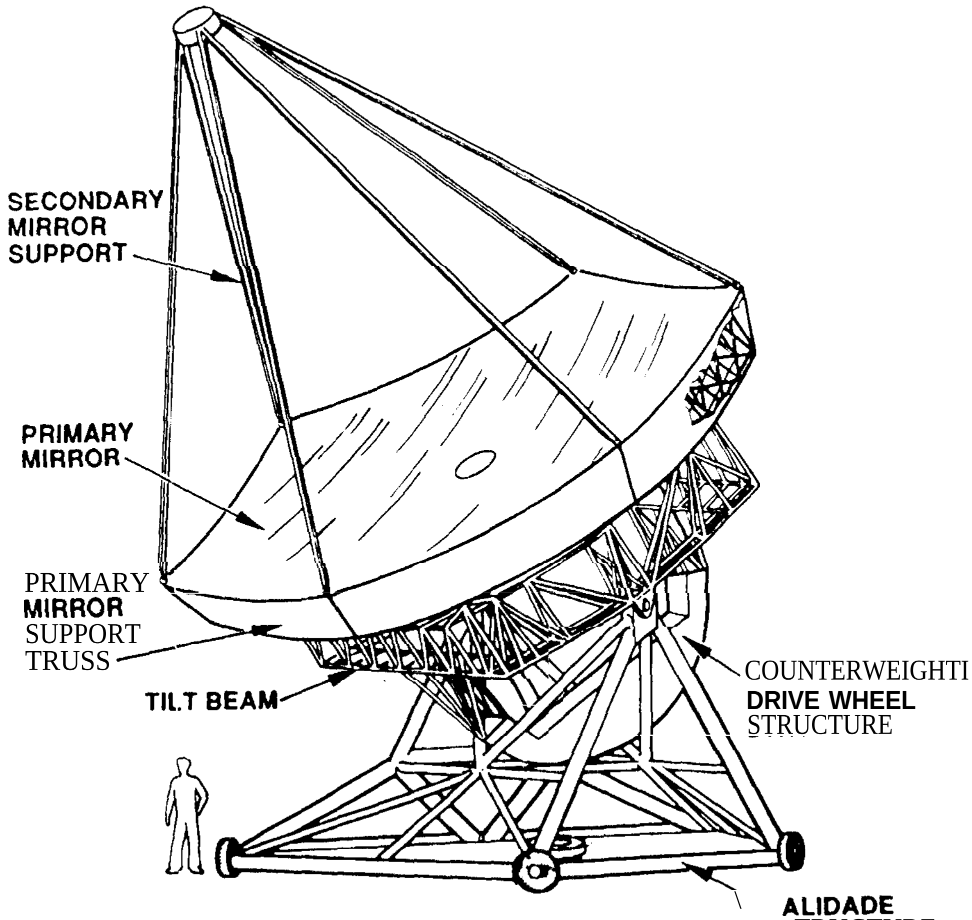


Figure 1. BT'OS telescope configuration

The overaH design of the BTOS structure has not been finalized, A preliminary configuration was developed and analyzed in an early study phase and is shown in Figure 1.[2] In the development of the preliminary configuration, certain assumptions were made to proceed with the design. The main assumption was the presence of an enclosed dome structure which utilized a thin transparent window to contain a dry nitrogen atmosphere, This helps to minimize thermal blooming effects. This dome effectively eliminated wind buffeting and was able to be closed shut during inclement weather. Also, inside the dome, an atmospheric control system was assumed to effectively circulate the dry nitrogen atmosphere to further reduce the thermal blooming effects, The dynamic effects caused by this circulating system have not been considered in the design of the primary mirror support structure,

Because the design of the entire BTOS structure has not been finalized, assumptions were made regarding components other than the primary mirror support structure have been made. First, the secondary mirror support structure has been modelled as a six beam graphite-epoxy structure supporting the secondary mirror substructure at three points. The tapered, rectangular beams were sized to provide a stiffness of over 10 cycles per second in a fixed/pinned boundary constraint. The beams arc pinned in the tangential direction, and fixed in the longitudinal direction. Second, the 90 hexagonal graphite-epoxy composite mirror support panels (1.3 meters flat-to-flat) arc assumed to be attached to the primary mirror support structure utilizing a near perfect kinematic mount system. The preliminary support system includes three sets of bipeds which can resist axial and tangential motion, but are flexible in the radial and rotational degrees of freedom. Thii kinematic system results in a support structure design that can remain independent of the mirror substructure panel design. Third, the tilt beam and alidade structure have been ignored, It is felt that by providing four supports each capable of only axial and tangential restraint, that the secondary effects caused by the stiffness of the tilt beam and alidade structure would be negligible. This assumption is made more plausible by recognizing the presence of a separate metrology system that can selectively deform the 90 individual mirror substructure panel attachments in order to correct for thermal and gravitational deformations. By making the above assumptions, the. design for the. primary mirror support system can begin.

The first consideration involves the stiffness of the support structure. Requirements have not been established for the fundamental frequency of the primary support structure. The preliminary design of the entire BTOS structure showed major modes of the primary mirror/secondary mirror supports starting at 6.8 hertz. The static deflections associated with the design were determined to be reasonable. Also, it was felt that the modal frequency of the major components had sufficient separation to help minimize dynamic interaction with the mirror segment control architecture. The new design must meet or exceed a fundamental frequency of 6.8 hertz.

The second consideration is with regards to thermal performance. The figure of the entire primary mirror must be held extremely accurately during all temperature ranges. The small gaps between segments must be maintained duc to the sensitivity of the edge sensors. For simplicity and cost savings, the metrology system for the mirror substructure panels can compensate for only motions normal to the surface. Therefore, radial deformations due to temperature variations can be minimize.d only by the primary mirror support structure. The ncw design must minimize in-plane motion duc to thermal extremes and gradients.

The third consideration is the requirement to survive gravity loads and other environmental loads such as turbulence or carthqr-rakes. For safety reasons, a factor of safety of 3.0 was self-imposed on the design to account for these effects,

4. FABRICATION ISSUES

Early in the design phase for the primary mirror support truss, cost was identified as a major concern. Steps leading to the final design must deal with issues such as a simple repetitive design, minimizing the number of elements, simplified assembly procedures, low procurement costs for piece parts, and the ability to accept a less than perfect structure..

Onc major flaw from the preliminary design work done in 1992, was the lack of simplicity in the primary mirror support truss design. The design work done favored an arrangement of struts that featured a symmetric top chord system but forced the bottom chord arrangement to be complex. Also the number of struts for that design was more than 1300 t ube assemblies, with five different cross-sectional areas. Upon revisiting this arrangement, a great ly simplified design was developed, as described in the next section,

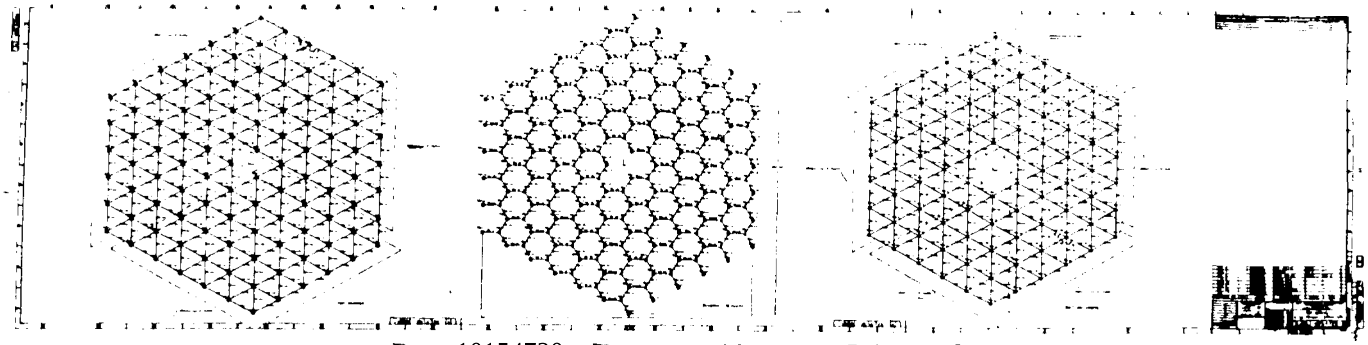
Assembly costs can often times be greater than the piece part costs of individual components, For this reason, special attention must be given to the method of assembly. Eliminating tooling costs ean save money directly, if a satisfactory method of producing a reasonable quality part can be found. By automating the assembly procedure at the individual subassembly level, a great deal of assembly time (and cost) can be saved,

Drilling holes in the field can be extremely expensive. Assuring high quality of the holes with regards to tolerances could be impossible. By pre-drilling holes in a controlled environment, the quality of the subassembly ean be ensured, while at the, same time giving the crew which assembles the entire structure a head start towards final alignment,

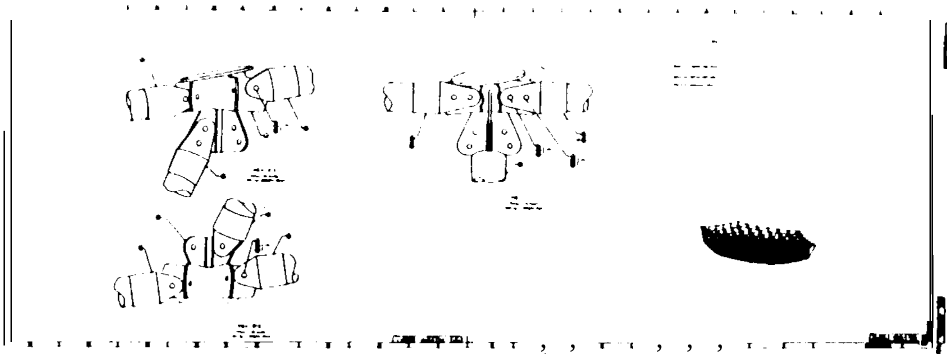
Finally, accepting the fact that a finished interface can be carefully controlled through the use of variable thickness shims, allows the remainder of the structure to be less than perfect during the assembly process. Also, a design which allows for small tolerance errors will help minimize the amount of rework during the assembly process. This type of joint must be capable of resisting the loads without slippage.

5. PRIMARY SUPPORT CONFIGURATION

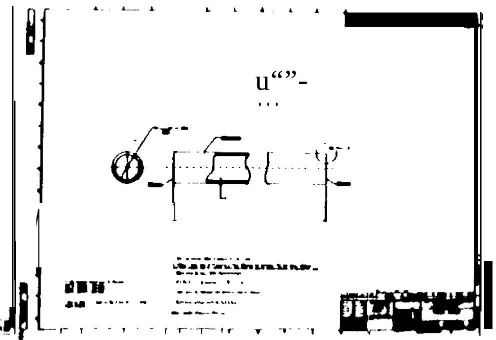
This section presents the results of a few months of concentrated effort to design a primary mirror support truss system for the BTOS structure. All of the issues and concerns mentioned above were taken into account when deciding the final design. Once analyses were completed, layouts were produced, It was at this stage of the design when the complex issues of fabrication, including piece parts, subassemblies, and final assembly, were worked to their conclusion.



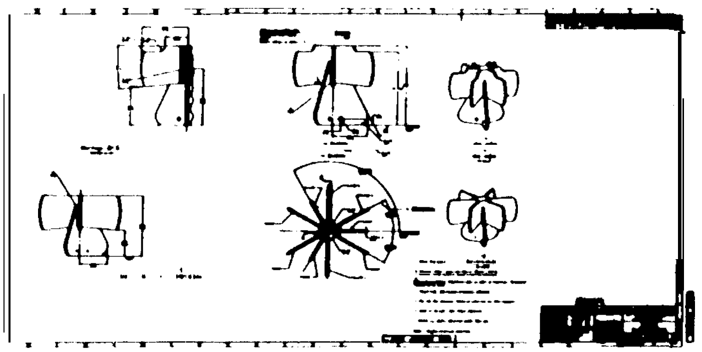
Dwg. 10154720 - Top Assembly, BTOS Primary Structure



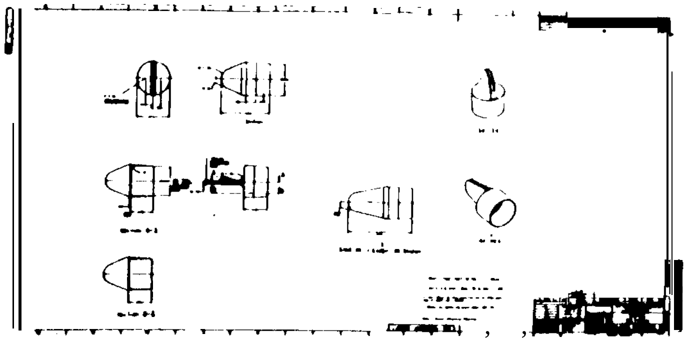
Dwg. 10154720 - Sheet 2



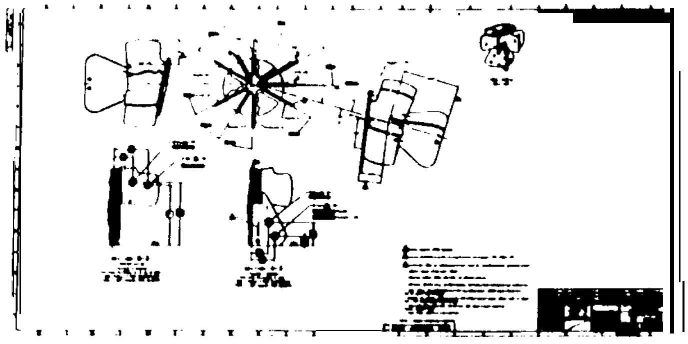
Dwg. 10154713- Tubes, Strut



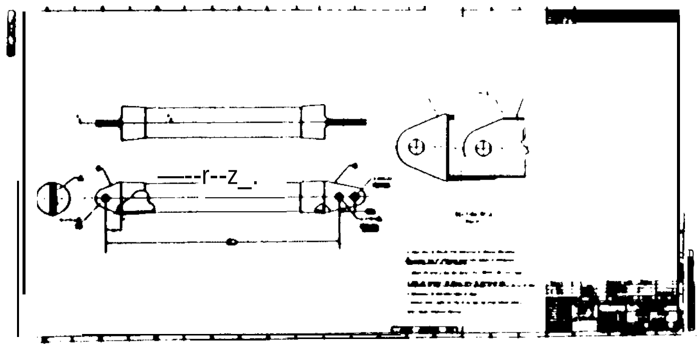
Dwg. 10154707 - Casting, Cluster Fitting



Dwg. 10154708 - Casting, End Fitting



Dwg. 10154709 - Cluster Fitting, Top - Machined



Dwg. 10154716 - Assembly, Strut, Single-Double

Figure 2. Reproductions of finished drawings

Selected drawings arc shown in Figure 2. These drawings are shown to convey the idea that this project is ready for production, and that all the detailed assembly and fabrication issues have been resolved. As the fabrication proceeds, changes to these drawings arc possible, and will be incorporated at the end of the production phase.

5.1 Design and fabrication

Early in the new design phase, it became apparent that if the number of mirror support panels was decreased, that the total number of tube assemblies could be decreased. By increasing the size of the panels from 1.0 meter flat-to-flat to 1.3 meters flat-to-flat, and by improving the arrangement of the panels, the number of panels decreased from 136 odd-shaped panels to 90 identical panels. This led to a decrease in the quantity of tube assemblies from over 1300 to **789** tube assemblies.

After assuming certain thicknesses for the mirror segments and the composite mirror support panel, a set of intersection points were created that became the centerlines for all intersecting tubes at each joint. A space of 11.00 inches was chosen, knowing that this value could be achieved using off-the-shelf actuators for the metrology syst em. Once the first intersection point was established, all other intersection points were instantly known because from the top view, all intersection points lined up to form perfect isosceles triangles. The height of the intersection points (relative to the central vertex) was established by maintaining an 11.00 inch offset normal to the true parabolic surface of the primary mirror segments. The lengths of the top and bottom tube assemblies vary by small amounts to account for the changes in angles. The depth of the truss remained nearly constant because the bottom surface was formed by projecting the top surface down by 60 inches, therefore the lengths of the diagonal tube assemblies arc similar.

Once the geometry was established, a finite element model was developed to determine the necessary cross-sections, A preliminary selection of three cross-sectional areas was chosen. Based on the preliminary work done earlier, it was felt that the material of choice was a pultruded graphite-epoxy matrix for the tube with bonded stainless steel end fittings. A value of 17,3 x 10^6 psi was estimated for the Young's modulus of the tube. The tube fiber layup consists of Hercules AS4 Carbon filaments with a vinylester matrix, The fibers arc at least 90% unidirectional with 10% or less consisting of a matted fiber matr ix on the outside to facilitate handling/fabrication loads. The tube has 62% fibers by volume. The vinylester resin was chosen over an epoxy matrix because it has a longer period of stable viscosity (3 to 5 days versus 6 to 12 hours) and has greater shrinkage which aids in mold re.lease? To help reduce the costs for utilizing multiple cross-sectional areas, the entire truss was assumed to only have three different cross-sections. The initial selections which met the frequency requirements are 3.00" outer diameter with .100" wall, 3.00" outer diameter with .1 so wall, and 3.00" outer diameter with .300" wall. Section 5.2 discusses the preliminary analyses.

The method of production for the end fittings became clear when the quantities of end fittings was known, Because. all the outer diameters of the tubes were identical, all the fittings could also be identical. The exception to this is that the top ends of all the diagonal tube assemblies and some of the top chord tube assemblies required a double bolt connection to resist some moderated bending moments. A total of 300 double bolt end fittings and 1278 single bolt fittings are needed for the finished assembly. Casting the 15-5PH st sinless steel fittings heat treated to H1 150 and using thcm essentially in the as-cast condition was considered to be the lowest cost approach. An inexpensive finish machine cut of the inner diameter of the tube socket was the only machining required. After the end fittings were bonded to the tube using epoxy, the holes are then precision drilled to the exact center-to-center required length, The holes are standard drill sires for a 3/4" diameter bolt, Due to the large size of the fastener, the estimated preload in the joint will prevent slippage of the part during operation.

The design of the cluster fitting.. was much more complicated. Because the top fittings provided the interface to the 90 mirror support panels, the top face had to be cut at a precise angle which was normal to the paraboloid surface. This led to .36 d ifferent finished fitting designs. However, the attachment of the nine tube assemblies was very repetitive except for small changes in the position of the bolt holes. After many methods were discussed, the outline below briefly describes the fabrication method for the 198 individual cluster fittings. The repetitive design features of the cluster fittings demanded that a casting process be employed. The steps which led to the finished machined cluster fittings is outlined below. It should be noted that 86 of the bottom cluster fittings did not require an interface "cap" plate.

a) Inspect and deburr the castings (108 top and 90 bottom).
b) Machine bottom surface flat and perpendicular to vertical axis.

c) Machine top of fitting to desired angle.
d) Weld 6.00" diameter laser cut cap plates to top surface.
e) Heat treat part to HI 1 SO.
f) Finish cut top surface. and drill a centering hole.
g) Secure part to a "rotisserie" tool which allows for precision drilling of the holes in each of the nine flanges.
h) Deburr and clean.

Final assembly of the structure is anticipated to be rather simple. Since all the holes are pre-drilled in the cluster fitting and all the center-to-center tube lengths are precision drilled, the amount of time spent machining the structure will be negligible. The tube assemblies and cluster fittings will be initially assembled with very low torques applied to the bolts. At selected intervals of the assembly, precision measurements of the top surface centers will be made to determine deviations from the desired paraboloid shape. Once the tops are in position, the final high torque values will be applied. Disassembly and reassembly of the entire truss will be required for shipment to various testing and operational sites. Only a limited number of joints will need to be disassembled.

5.2 Structural analyses

To aid in achieving the optimal design for the primary mirror truss, a MSC/NASTRAN model was developed. It accurately represented the individual tube assemblies and lumped the mass of the 12087 pound mirror/mirror support panels into 108 locations. The secondary mirror support structure was also included. A total of 908 elements and 322 grids were utilized. Figure 3 shows a plot of the finite element model. Figure 4 shows the location of the three different tube sizes used in the design. The heaviest tubes are located near the four attach points to the tilt beam and the six secondary mirror supports. Analysis shows that the design has a fundamental frequency (when pinned at the tilt beam interface at four places) of 7.7 hertz and is basically the secondary mirror moving side-to-side causing the primary mirror support structure to "potato chip". Some selected modes are listed below:

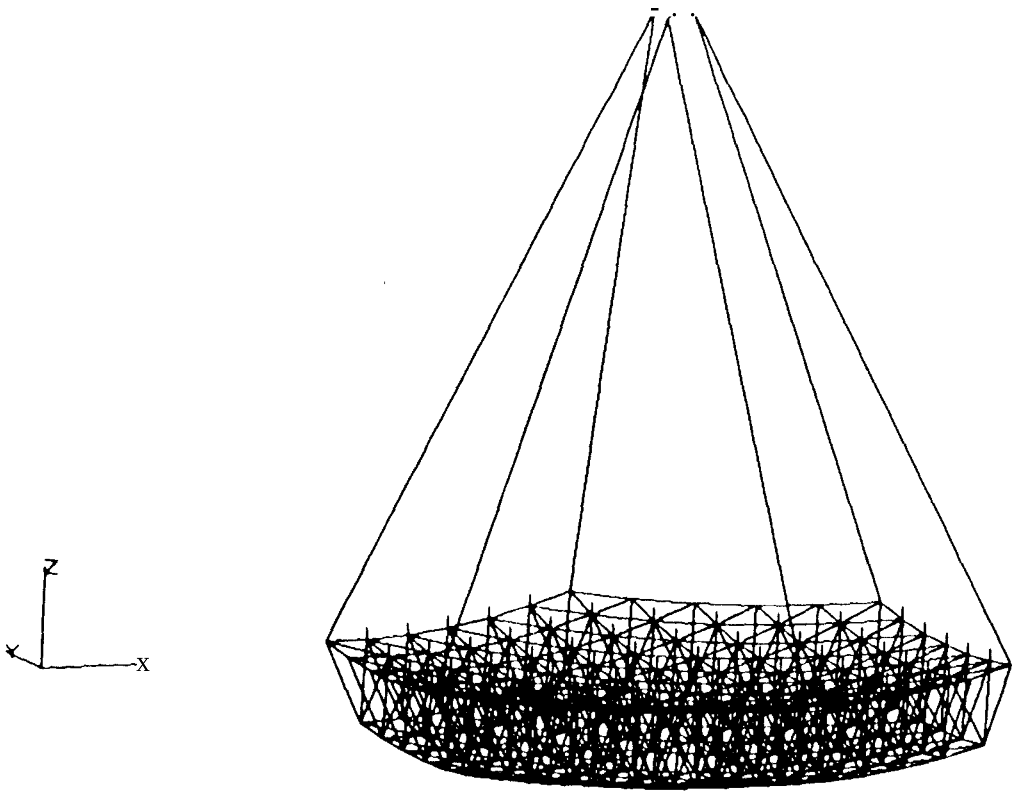


Figure 3. Plot of primary and secondary mirror support finite element model

Mode	Frequency	Description
1	7,71 Hz	Secondary +X/+ Y motion with Primary support potato chipping
2	7.88 Hz	Secondary +X/-Y motion with Primary support potato chipping
3	8,21 Hz	Secondary twisting about Z axis
4	9.31 Hz	Secondary twisting about Z axis with some lateral motion
6	9.67 Hz	Secondary support beams bending in weak axis
10	13.09 Hz	Secondary support beams strong axis with Primary support tubes near the six corners exhibiting strain
13	16.36 Hz	Primary support potato chipping with secondary mirror X motion
15	20.42 Hz	Primary support potato chipping with secondary beams exhibiting complex bending in weak axis

The highest stresses for the assembly occur in the bond between the end fittings and the tube, The highest stress in the bond is estimated to be 1295 psi. This assumes a factor of safety of 3.0 and given a conservative epoxy bond allowable strength of 1800 psi gives a margin of safety of 0.38 which is adequate. Stresses in the steel end fittings arc. low (23500 psi) and stresses in the cluster fittings are higher at 84,000 psi but still within the allowable of 105,MKI psi for the 15-5 PH HI 150 stainless steel, It should be noted that after the analysis was completed, a design change to eliminate the smallest cross-section tube (.100" wall) and replace it with the. medium size tube (,150” wall) was done in order to save costs for production of the tubes. This will produce a small increase in the overall stiffness of the support truss.

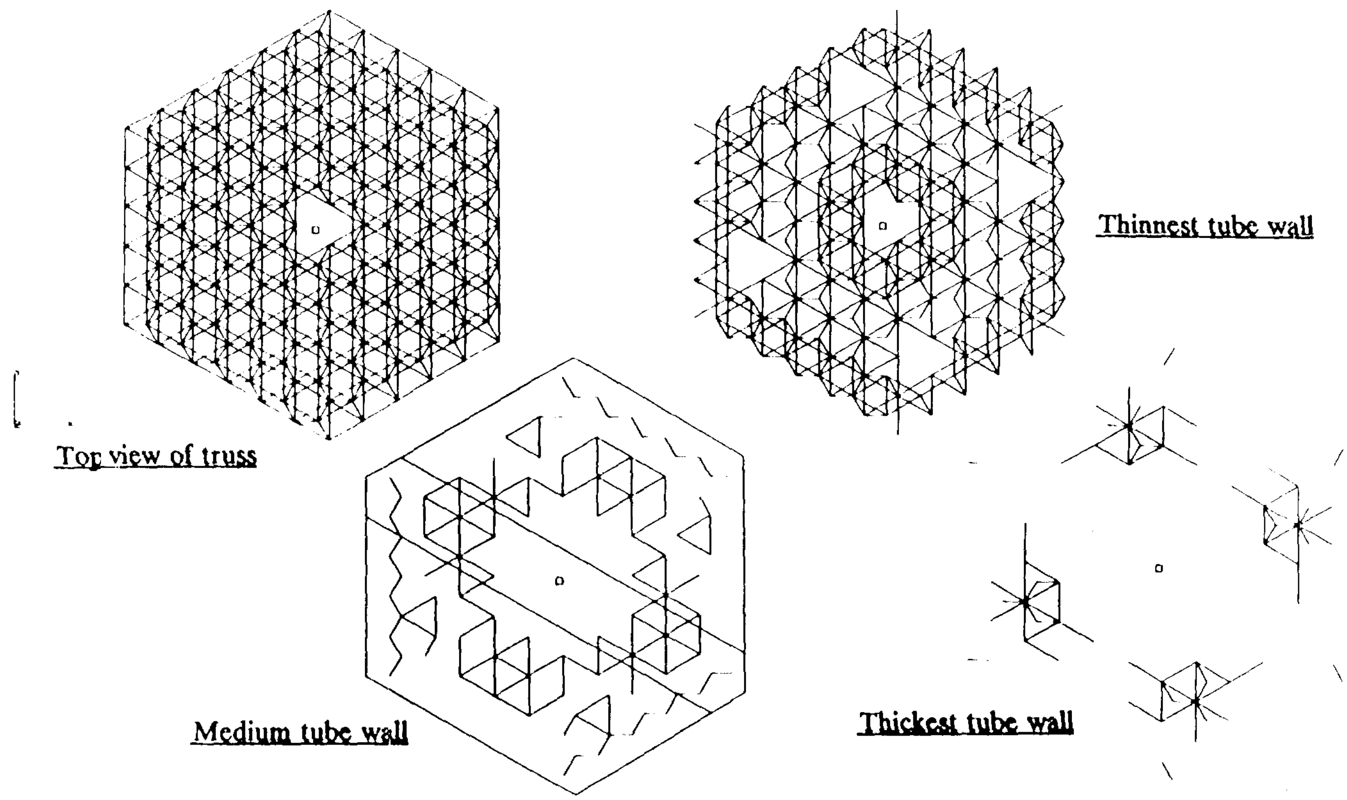


Figure 4. Relative location in truss for three different tube cross-sections

6. SUMMARY

The primary mirror support truss for the BTOS project has been designed with many issues taken under consideration. The design first addressed strength, temperature, and dynamic requirements. The concerns for low cost production required that the design pay special attention to reducing complexity of the design, minimizing labor intensive steps, and taking advantage of repetitive piece part production. The results of complete structural analysis and many detailed discussions with the assembly, material, and fabrication groups arc documented in the form of released production drawings. Marshall Space Flight Center has undertaken the task of procuring all piece parts and assembling the truss. Production of the composite tubes has begun, with completion of the entire primary mirror support truss expect cd in 1994.

7. ACKNOWLEDGEMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under a contract with the National Aeronautics and Space Administration.

The authors wish to gratefully acknowledge the contributions provided by many of our colleagues at JPL and other centers and outside organizations. JPL contributions from Bob Bamford (structures), Cheng Hsieh (materials), Lany Lafferty (design production), Bill Layman (design), Roy Levy (t elescope design), David Miller (design), George Sevaston (project manager), and Don Trujillo (fabrication). Marshall Space Flight Center contributions from Whitt Brantley (design), Bill McMahon (composites), Sandy Montgomery (project manager), John Redman (structures). Outside cont ribut ions from John Doyle and Vern Kallenborn of D. F. 1, Pultruded Composites, Inc., and Jess Jaros of Fenico Precision Castings, Inc. A final acknowledgement goes to Dr. John Rather of NASA Headquarters for inspiring this project,

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