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HUGHES DANBURY OPTICAL SYSTEMS, INC.
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PR D15-0015

LUTE TELESCOPE STRUCTURAL DESIGN STUDY REPORT

MAY 1993

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35812

Order No. H-19671D

HUGHES DANBURY OPTICAL SYSTEMS, INC.
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Project Report No.: PR D15-0015

Title: LUTE Telescope Design Study Report

Prepared by: Greg Ruthven, Project Engineer — 7/9/93 Date

Approved by: Mark Stier, Program Manager — 9 July 93 Date

Approved by: George Bossers, Director, Advanced Development Lab — 7/16/93 Date

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SECTION 1

INTRODUCTION

The major objective of the Lunar Ultraviolet Transit Experiment (LUTE) Telescope Structural Design Study was to investigate the feasibility of designing an ultra-lightweight 1-m aperture system within optical performance requirements and mass budget constraints. This study uses the results from our previous studies on LUTE as a basis for further developing the LUTE structural architecture.

After summarizing our results in Section 2, Section 3 begins with the overall logic we used to determine which telescope "structural form" should be adopted for further analysis and weight estimates. Specific telescope component analysis showing calculated fundamental frequencies and how they compare with our derived requirements are included. "First-order" component stress analyses to ensure telescope optical and structural component (i.e. mirrors & main bulkhead) weights are realistic are presented. Layouts of both the primary and tertiary mirrors showing dimensions that are consistent with both our weight and frequency calculations also form part of Section 3.

Section 4 presents our calculated values for the predicted thermally induced primary-to-secondary mirror despace motion due to the large temperature range over which LUTE must operate. Two different telescope design approaches (one which utilizes fused quartz metering rods and one which assumes the entire telescope is fabricated from beryllium) are considered in this analysis. We bound the secondary mirror focus mechanism range (in despace) based on these two telescope configurations.

In Section 5 we show our overall design of the UVTA (Ultraviolet Telescope Assembly) via an "exploded view" of the sub-system. The "exploded view" is annotated to help aid in the understanding of each sub-assembly. We also include a two view layout of the UVTA from which telescope and telescope component dimensions can be measured.

We conclude our study with a set of recommendations not only with respect to the LUTE structural architecture but also on other topics related to the overall feasibility of the LUTE telescope sub-system.

SECTION 2

SUMMARY OF RESULTS

Based on this and the previous LUTE study, we remain convinced that the ability to design, build, test and successfully launch and operate a 1-meter class diffraction limited telescope operating over a large temperature range appears to be feasible. The major thrust of this study was to show that the telescope structural form or "architecture" could meet its weight and frequency allocation while still meeting its optical performance requirements. We have shown the weight and frequency requirements to be achievable by fabricating the telescope from beryllium. We have also taken advantage of a telescope architecture which allows efficient use of the available weight by designing deterministic load paths which results in non-complex telescope interfaces. The secondary mirror focus mechanism range is dependent on a number of error sources which have been identified. We have estimated that the anticipated range is well within that currently available (e.g. Hubble Space Telescope) and therefore does not represent a technology risk to the LUTE program.

After evaluating a number of telescope structural architectures we believe that a telescope which uses an "inverted tripod" metering structure in concert with a "single taper" primary mirror design can meet the stringent telescope sub-system weight requirement of 84 kg even assuming a 18% weight contingency factor. Our calculated telescope sub-system weight is 83 kg including this factor. By adopting this design approach significant weight savings are realized in the areas of the telescope light baffle and main bulkhead. This design concept not only meets the weight requirement but meets the derived telescope fundamental frequency requirement of ≥ 50Hz. This design also affords us the ability to assemble and align the telescope subassemblies "off-line" so that parallel integration activities can take place.

As mentioned in our previous LUTE study, the extreme temperature range (± 100 K) over which the telescope must operate represents a significant challenge in terms of meeting wavefront requirements. Assuming this temperature range the secondary mirror focus mechanism should have a minimum despace range (i.e. travel along the optical axis) of approximately ±1 mm. As a point a reference, the HST focus mechanism has a range of approximately ± 3 mm.

SECTION 3

UVTA DESIGN DESCRIPTION AND STRUCTURAL ANALYSES

3.1 STUDY LOGIC

The logic used to assess the structural design of the Ultraviolet Telescope Assembly (UVTA) is shown in Figure 3-1. We relied heavily on the results from the MSFC LUTE Interim Technical Assessment Report and the HDOS LUTE PM Material & Design Study to formulate this logic. This included the assessment of the MSFC telescope structural architecture in terms of both weight and fundamental frequency performance. The results of the Hubble Space Telescope-like metering truss design approach used in the MSFC baseline design were used as a benchmark and point of departure for our study.

Based on prior programs such as the Orbiting Solar Laboratory (OSL) where we studied several structural forms for a 1-m telescope, we qualitatively knew the performance of a "ring-stiffened" metering structure as compared to the HST type structure. We therefore focused our attention on two other metering structure designs. The first was a metering bar approach where low coefficient-of-thermal expansion (CTE) material is used to maintain PM-to-SM spacing while decenter errors are minimized via a set of axial and tangential flexures. This structural configuration allows the use of high CTE material (e.g. beryllium) to be used for the load carrying structure.

The other configuration we investigated we termed an "inverted tripod" design where the secondary mirror assembly (SMA) is supported via a metering structure which utilizes the "real estate" between the PM and tertiary mirror (TM). This design approach has a disadvantage in that the metering structure locally obscures a small portion of the converging optical beam at three locations. This is in contrast to a more conventional telescope design which utilizes a SM spider. However we have qualitatively discussed these effects and have determined this design approach to be acceptable.

Our assessments of these two configurations were done in a serial logic form. We made calculations to assess the metering bar and went through the logic "gate" on whether this design option was warranted for further study. We concluded that with the baseline beryllium optics which we recommended in the PM Design Study, a metering design approach to the LUTE telescope did not display any advantages

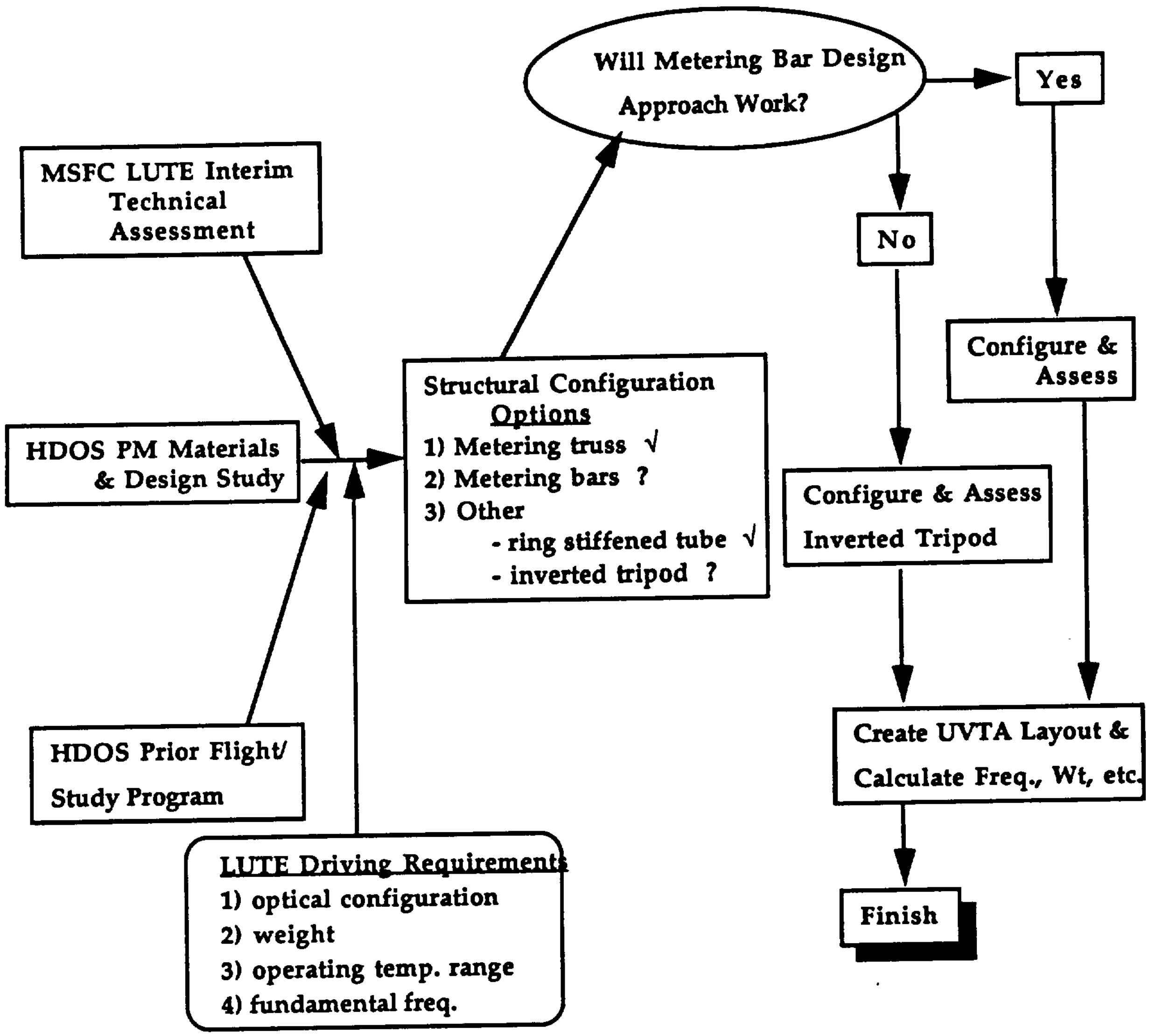


Figure 3-1. Telescope Structural Configuration Trades Conducted in Order to Meet Strawman Set of Requirements.

(this is discussed further in Section 4). We therefore assessed the inverted tripod design and concluded that, to first order, this design will meet the optical performance, weight and fundamental frequency requirements shown in Table 3-1.

TABLE 3-1
A CONSISTENT SET OF REQUIREMENTS HAVE BEEN MAINTAINED THROUGHOUT THE LUTE STUDIES

• Optical Design	• 3 mirror telescope • Diffraction limited @ 0.63 μm • 1 meter diameter C.A. • Operating W.L. = 0.1-0.35 μm
• Telescope Weight	• ≤ 84 kg
• Operating Temperature Range	• 260K - 60 K
• Fundamental Frequency	• Telescope: > 50 Hz • Primary Mirror: > 150 Hz

The inverted tripod design "cut-away" isometric layout is shown in Figure 3-2. There are several design features worth noting. The first is the ability of this design to meet its weight allocation of ≤84 kg. This is possible because of the significant lightweighting possible of the telescope main bulkhead which acts as both the telescope "backbone" along with the interface structure for the telescope hexapod actuators. This lightweighting is made possible only by the implementation of the single taper PM design. This PM design locates the PM mirror mounts at the inner hole ID and therefore the main bulkhead top faceplate can be relatively small in diameter. The second weight benefit of the inverted tripod design is that the telescope light shade is no longer a load carrying structure. It does not need to support the 10.5 kg SMA but only its self weight.

Sections 3.2 through 3.6 will describe each of the major sub-assemblies and/or components and give results of weight calculations, fundamental frequency and "first order" stress calculations due to launch vehicle ascent loads. We summarize the UVTA telescope weight estimate with particular attention to the weight associated with the "structural" components.

3.2 PRIMARY/TERTIARY MIRRORS

During our LUTE PM Study we tentatively concluded that an integral PM/TM design was preferable. Consultations with our optical fabrication personnel indicated that in fact the fabrication of this mirror is feasible.

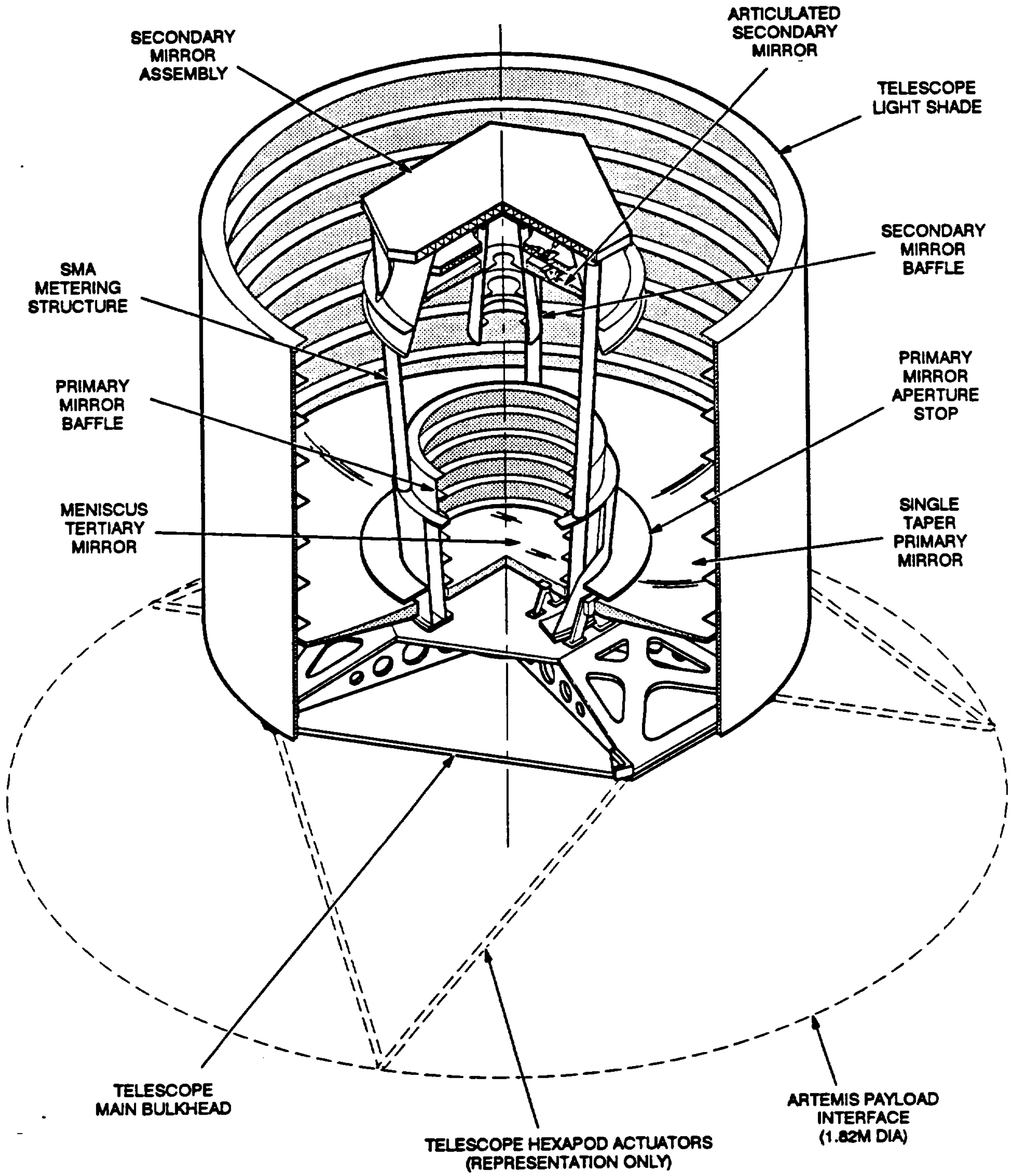


Figure 3-2. Our Lute Telescope is Based on a 3 Mirror Optical Design and a Very Aggressive Weight Budget.

Based on the decision to baseline the inverted tripod metering structure design we have reassessed our original conclusion. Aside from the configuration decision there is a weight penalty associated with an integral PM/TM design. For our single taper mirror design with an inner "hub" thickness of 25 mm, the weight of the portion of the mirror which is a "non-optical" (i.e. an annulus with an OD = 474 mm and an ID of 306 mm) is approximately 5 kg. Assuming the weight allocation of 2.3 kg for the PM mounts would be adequate to accommodate both this increased weight and the weight of the TM, a savings of 0.9 kg would be realized because the TM mounts would no longer be required. The net weight increase to the telescope system would be 4.1 kg, or an increase of 6%.

Figures 3-3 and 3-4 are the LUTE primary and tertiary mirror layouts. The PM is supported by three sets of bipod flexures fabricated from titanium with a thickness of 2.5 mm and a width of 12 mm. The TM is supported by a similar set of flexures. Both mirrors are fabricated from beryllium and each slightly oversized to accommodate edge rolloff effects and beveling during fabrication. We have assumed 10 mm margin for rolloff and 3 mm for beveling (both on the radius). The weights are 22 kg and 3 kg for the PM and TM, respectively.

NASTRAN analyses of these mirrors indicate their frequency requirements are met with margin. These requirements are specified in Table 3-2. Assuming a fixed base, three point attachment to the mirror, the fundamental frequency of the PM and TM are 260 and 1950 Hz, respectively. The hand-calculated maximum stress levels in the mirror assuming a 15 g rms ascent load with factors of safety (FOS) of 1.25 and 1.5 for yield and ultimate are 2700 and 800 psi, respectively.

Our PM design is of a similar form of that which HDOS fabricated and which was subsequently cryo tested at Ames Research Center (ARC) in the 1987-1988. That mirror, fabricated from optical grade I-70A hot isostatic pressed (HIP) beryllium was a 0.5 m diameter optic with an areal density of 28 kg/m^2 and was tested at 80 K and 8 K. The room temperature (293 K) figure was ~0.06 waves rms @ 0.6328 μm and the cryo distortion transitioning from 293 K to 80 K was 0.21 waves rms.

3.3 SECONDARY MIRROR ASSEMBLY (SMA)

The SMA is composed of the secondary mirror (SM), a set of actuators to provide 5 degrees-of-freedom for the SM, a SM hub which reacts the loads imparted to the SM, and the SMA hub which is the main load carrying member of the SMA The SMA hub also provides the interface to the metering structure. The SM baffle will be discussed in Section 3.4.

The SM design is essentially the same as we are using for the TM. That is, a HIP'd beryllium meniscus mirror with a thickness of 12 mm with the same "overage" to account for rolloff and beveling. "Pockets" at three locations on the rear or "R2" surface of the mirror allow the mirror to be supported as close to its center-of-gravity

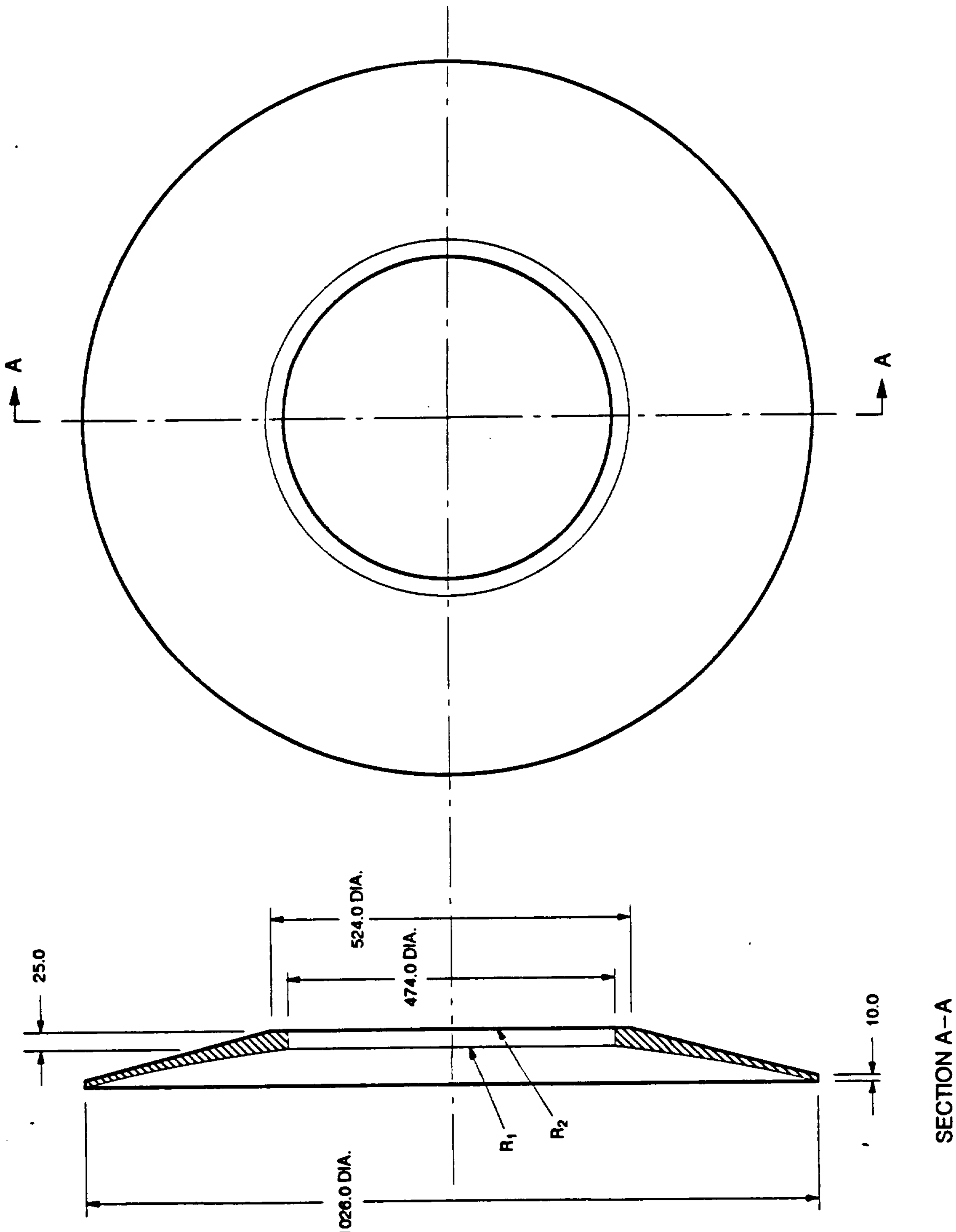
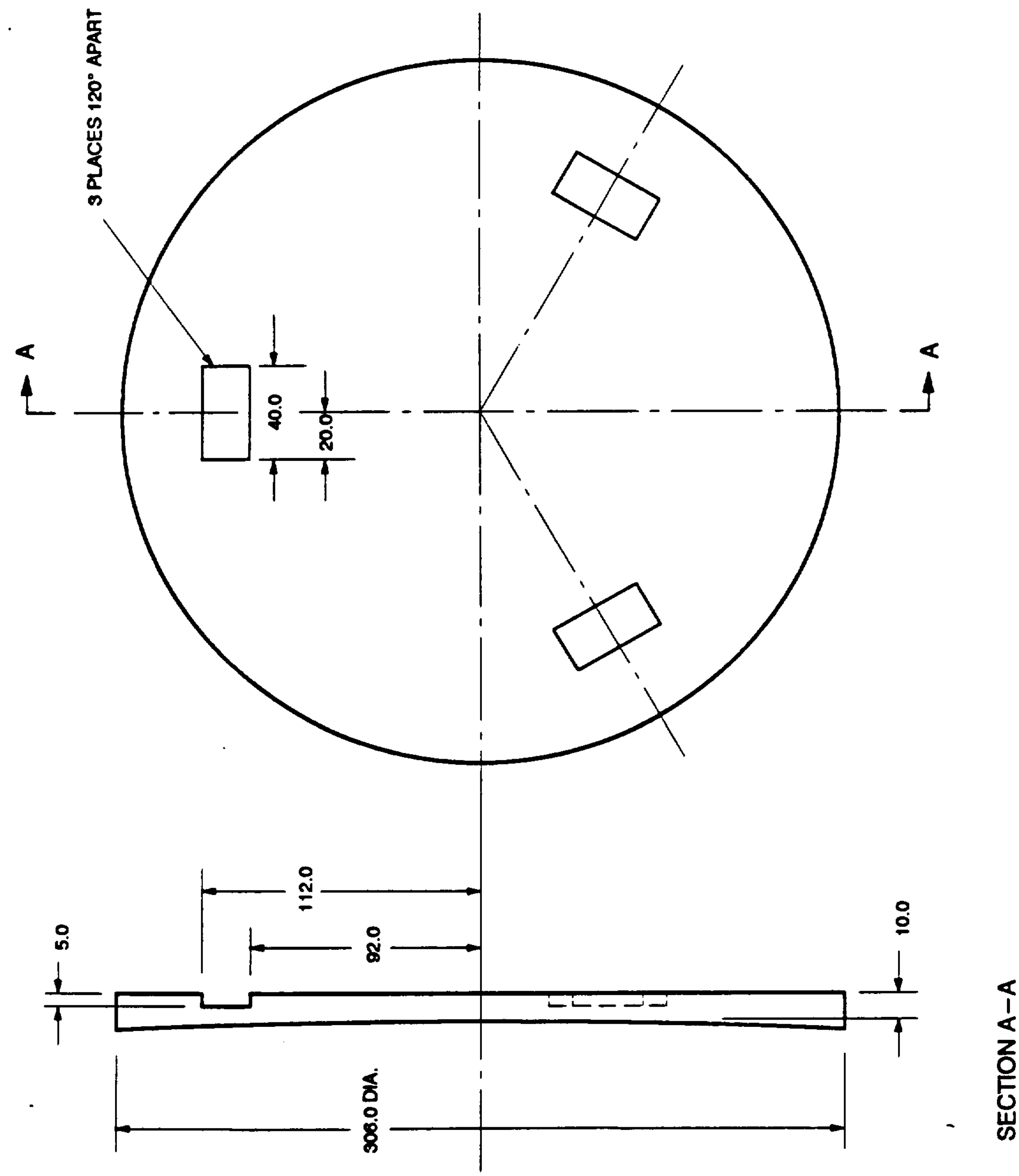


Figure 3-3. 1.03 Meter f/1.0 Lute Primary Mirror.



0.3 METER f/0.6 LUTE TERTIARY MIRROR

Figure 3-4. 0.3 Meter f/0.6 Lute Tertiary Mirror.

TABLE 3-2
FUNDAMENTAL FREQUENCY REQUIREMENTS BASED ON GROUND TESTING DIAGNOSTICS AND SPRING-MASS COUPLING

• Lute Telescope 50 Hz		
• Primary Mirror Assembly	100 Hz	
* Primary Mirror		150 Hz
* Main Bulkhead		500 Hz
• Secondary Mirror Assembly	300 Hz	
* Secondary Mirror		800 Hz
* SM Hub		500 Hz
* SM Delta Frame		500 Hz
• Metering Structure	60 Hz	
• Tertiary Mirror Assembly	500 Hz	
* Tertiary Mirror		1000 Hz

(CG) as possible via 3 sets of bipod flexures. Additional bending moments during ascent would cause the flexures to be heavier if we didn't employ these "pockets." A calculated first mode of 1045 Hz and a stress level of 6100 psi meets the requirements.

The SM hub and delta frame are both lightweighted designs which utilize a square core structure sandwiched between two faceplates that are 1.5 mm thick with an overall thickness dimension of 19 mm. This same type of construction was used on a number of components on the Visible/Ultraviolet Experiment telescope which flew in the late 1980's. The construction technique used to fabricate these sections was to EDM (electro-discharge machine) a number of small diameter holes in the faceplates and core structure and to lock wire them together during the brazing operation. The wires were removed after the brazing operation. Figure 3-5 is a photograph of the forward end of the VUE telescope showing two lightweighted bulkheads which are nominally 50 mm in depth. Brazed connection between the bulkheads and other telescope structure can also be seen along with local inserts in the core structure to accept threaded connections. Hand calculations to determine the fundamental frequency of the two LUTE 19 mm deep lightweighted structures show that the 500 Hz first mode requirements are met (800 and 725 Hz for the hub and frame, respectively).

3.4 BAFFLES

All of the UVTA baffles are fabricated from aluminum. We considered issues such as material size availability, the baffle not being a load carrying member (except its own self weight) and ease of fabrication when determining these designs. For instance, the main baffle could not be fabricated from a single sheet of beryllium.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

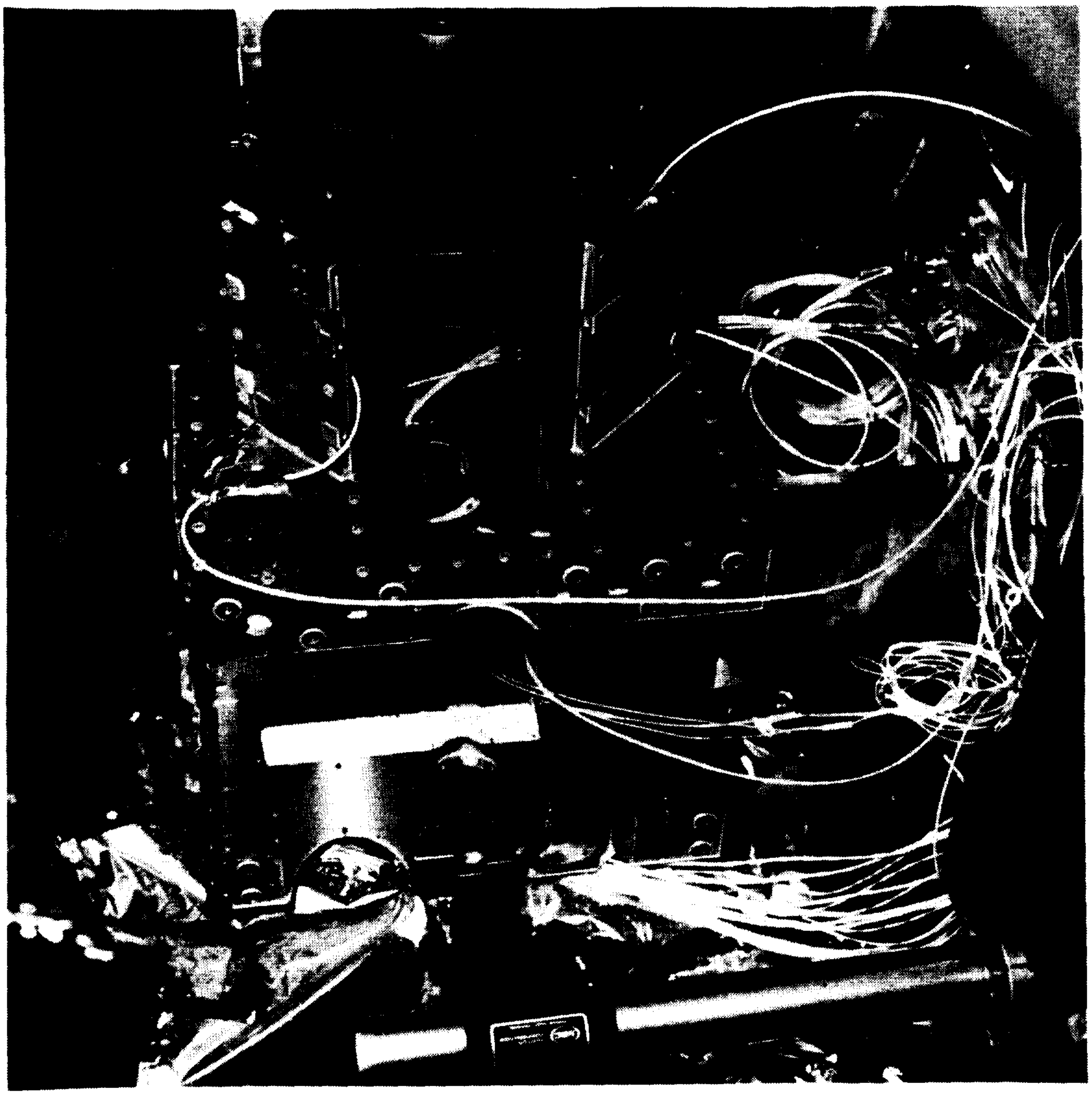


Figure 3-5. Beryllium Construction Techniques Successfully Employed on the VUE Telescope are Directly Applicable to Lute.

The main baffle is nominally 1120 mm in diameter and 960 mm in length. Its construction is a ring-stiffened structure with a wall thickness of 0.4 mm. Internal vanes which are 25 mm deep are attached to this shell and act as both structural stiffeners and stray light control vanes. Figure 3-6 is the NASTRAN modal analysis of this structure which shows a first bending mode frequency of 230 Hz and weight of 5.9 kg. This weight is slightly higher than the original estimate of 4.1 kg and is due to the further definition of the packaging requirements of the SMA.

Both the SM baffles are of similar construction to that of the PM baffle. Aluminum is again used for both SM baffles which are truncated cones with vanes located on the OD and ID. These baffles are attached the SM delta frame through a series of pinned and bolted joints. The combined weights of both of these structures is 2.1 kg.

The central baffle (primary baffle) has two functions. It's first function is to act as a stray light control component. We again have kept it's shell thickness the same as all other UVTA baffles. However this baffle also aids in the stiffening of the metering structure. In order to decrease the effective cantilevered length of the metering structure and thereby increase its natural frequency, we've connected the central baffle to not only the main bulkhead top faceplate but also the beryllium tubes which form part of the metering structure. As will be discussed in the next section, this "closes" the metering structure on its ID while a second stiffening shell, considered part of the metering structure assembly, "closes" the structure on its OD.

3.5 METERING STRUCTURE ASSEMBLY

Our inverted tripod structure takes advantage of the annular region between the PM ID and TM OD to package the metering structure. This structure is connected to the main bulkhead via an interface flange which is pinned and bolted to the top faceplate. Our current concept for this design is to utilize 6 beryllium tubes that are 34 mm in diameter with a wall thickness of 2.5 mm. These six tubes extend from the main bulkhead interface flange in a slightly canted orientation (i.e. the origin of the term "inverted") to a point approximately 240 mm from the main bulkhead interface. Three of the six structural tube members are terminated at this location to minimize distortion at the image plane due to this obscuration. The three members that are terminated are "capped" with three sections of an annular ring. These sections are brazed to the top of the members and to the periphery of the three structural members which continue up to the SMA. This adds significant rigidity to the structure. To further add stiffness of this structure an outer shell is attached to all six tube members. By designing this structure in this fashion the effective cantilevered length of the metering structure is significantly reduced.

NASTRAN analysis of this structure has been completed. Assuming that the cantilevered length is approximately 560 mm (the distance from the termination of three metering structure tube members to the SMA support location), and using the SMA calculated weight estimate of 7.2 kg, our analysis shows the first bending

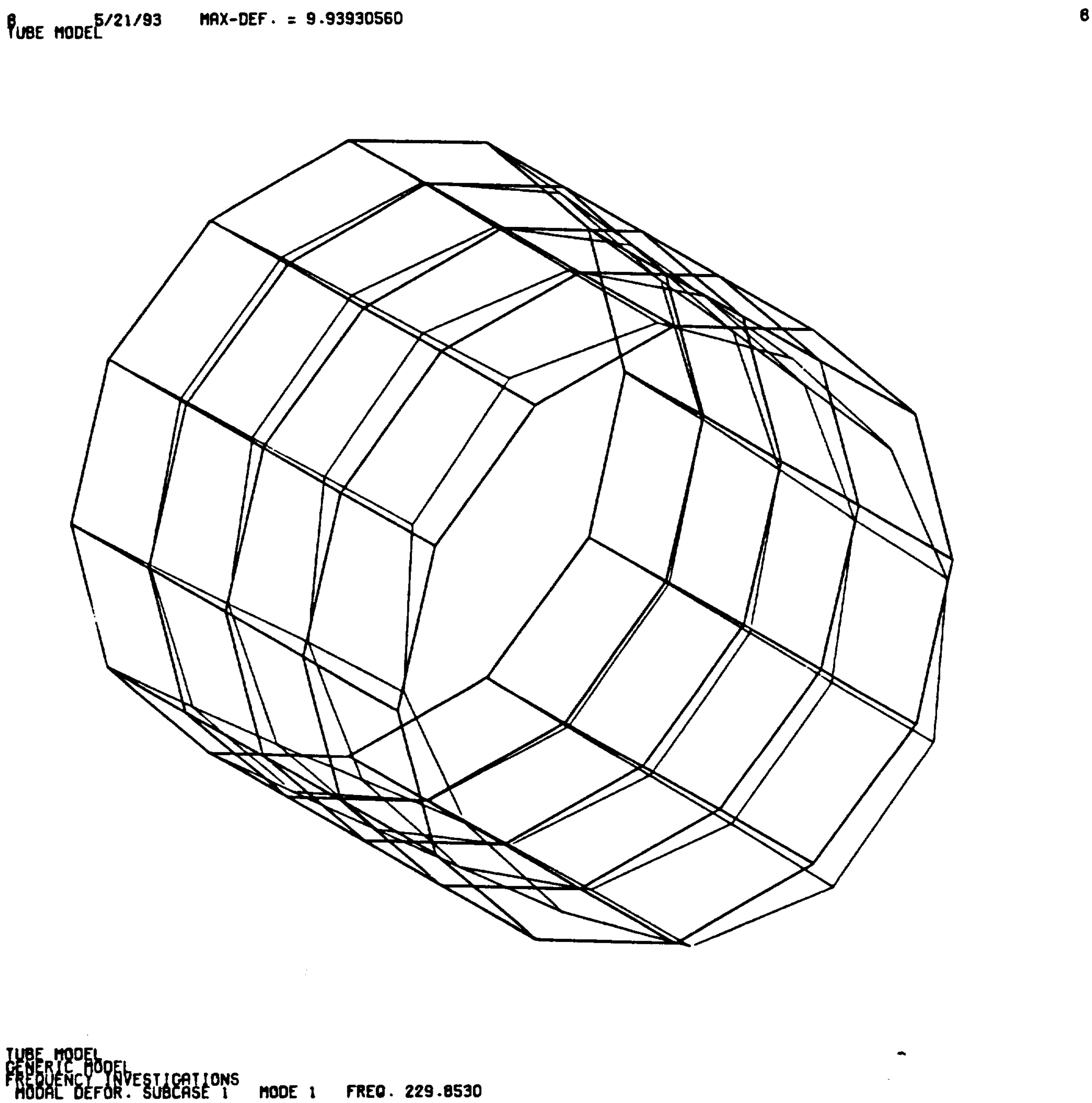


Figure 3-6. Results from Main Baffle NASTRAN Model Confirms design meets fundamental frequency requirements.

mode of the metering structure is 65 Hz. The first torsional mode of this structure is 104 Hz. The 60 Hz derived requirement is satisfied with this design approach and therefore we feel comfortable that ascent and lunar performance can be achieved.

The total weight of this structure is 2.2 kg which includes the weight of the 3 short and long beryllium tubes, the 3 annular ring "caps", the main bulkhead interface flange, and the 240 mm long metering structure closure cylinder. The "caps" and the interface flange are both 2.5 mm thick while the truncated cylinder is 1.3 mm thick. Hand stress analysis show that tube stress levels are low. A calculated stress of 9200 psi in a tube is well within the nominal values for yield and ultimate failure criteria for extruded beryllium structural shapes.

3.6 MAIN BULKHEAD

Our main bulkhead design is one of the major reasons why we feel that the 84 kg telescope weight requirement is feasible. To develop this concept we combined the fact that the PM single taper design requires its mounts to be located near its central hub and that the telescope main baffle must only be self supporting.

Lightweighting of this structure is evident. Minimization of weight is accomplished through the use of lightening holes and cutouts. Shear panels, which "beam" the loads from the top to bottom faceplates and then transfer these loads to the telescope hexapod actuators utilize these techniques. Three plates connecting the six shear panels have been designed to maintain structural stability while adding structural stiffness to the main bulkhead. These plates also have been lightweighted via "cutouts". The telescope main baffle only requires connection to the lower face-plate/shear panel locations at six locations due to its low weight. Local "L" brackets are used to make this connection through the OD of the main baffle. Where the main baffle is not connected to these six locations, non-load carrying secondary structure is used to control contamination and reflections off the lunar lander and/or surface. To facilitate PM and TM alignment, six local raised pads are located on the top faceplate of the main bulkhead. This allows tight tolerances to be maintained over a relatively small area.

The bulkhead is fabricated from beryllium. There are 3 "field splices" of the larger faceplate because of manufacturer limitations on maximum available size. These splices occur directly over three of the shear panels. All main bulkhead plate thickness are nominally 2.5 mm. Faceplate, shear panels and plates are brazed together to make a continuous, rigid, and deterministic structure. We used hand calculations to show that a first mode of 870 Hz and a maximum stress level of 5200 psi suggests this design is robust. We believe that more detailed analysis would continue to show this design meets its requirements.

3.7 WEIGHT ESTIMATES

The UVTA telescope weight estimates for the HDOS strawman design is shown in Table 3-3. This weight estimate reflects the updates to the original design concept use in the PM Materials & Design Study in terms of the metering structure, main bulkhead, baffles, and SMA. No attempt was made to assess the original allocations made to the electronics, alignment sensor and thermal control.

We have concluded that the original "structural" weight allocations are reasonable and except for some redistribution of weight, our original estimates were reasonable. There appears to be no outstanding issues with respect to launch survivability or dynamic characteristics which would indicate that these estimates will significantly increase.

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TABLE 3-3
LUTE CALCULATED WEIGHT ESTIMATES COMPARED TO ALLOCATIONS AND ASSESSED TO DETERMINE TELESCOPE FEASIBILITY

Major Element	Sub-Ass'y/ Component	Weight Allocation(kg)		Calculated Estimate (kg)	
1) Mirrors	Primary		21.8		21.8
	Secondary		2.7		2.7
	Tertiary		1.4		1.4
	Sub-Total:		25.9		25.9
2) Structure	Baffles:				
	Main	4.1		5.9	
	Primary		0.9		0.9
	Secondary		0.5		2.1
	Sub-Total:		5.5		8.9
	Mirror Mounts:				
	PM		2.2		0.9
	SM		1.4		0.7
	TM		0.9		0.7
	Sub-Total:		4.5		2.3
	Main Bulkhead S. Ass'y:				
	Main bulkhead		5.4		6.8
	S/C I/F fittings (3)	1.4		1.4	
	Sub-Total:		6.8		8.2
	Metering Struc. S. Ass'y:				
	Metering structure	1.3		1.5	
	I/F fittings (6)		1.3		0.7
	Sub-Total:	2.6		2.2	
	SM Sub-Assembly				
	Spider		1.8		0
	Spider flexures		1.4		0
	Delta Frame	1.4		1.3	
	Hub		1.4		1.4
	Actuators		2.7		2.7
	Cabling		1.8		1.8
	Sub-Total:		10.5		7.2
3) Electronics	ACE		1.2		1.2
	TCE		1.2		1.2
	DMS		1.2		1.2
	ASE		1.2		1.2
	Sub-Total:		4.8		4.8
4) Thermal Control	Heaters		0.9		0.9
	Thermocouples		0.9		0.9
	MLI		1.5		1.5
	Cabling		2.0		2.0
	Sub-Total:		5.3		5.3
5) Alignment Sensor	Sensor	3.5		3.5	
	Sensor mount	0.5		0.5	
	Sub-Total:		4.0		4.0
	Total (w/o reserve):	69.9		68.8	
	Reserve:		14.1		13.9
	TOTAL:		84.0		82.7

SECTION 4

PRIMARY-TO-SECONDARY MIRROR DESPACE PREDICTIONS

4.1 THERMALLY INDUCED

Early in the study we traded metering structure design options. Using the work completed and documented in the MSFC "LUTE Interim Report" with respect to the Hubble Space Telescope (HST) type metering truss design, we investigated two additional types of structures. The first is a metering bar design approach where low coefficient-of-thermal expansion (CTE) material (i.e. fused quartz) is used to maintain the spacing between the primary and secondary mirrors in the presence of bulk temperature changes. This design approach is beneficial when considering a telescope design whose bulk temperature change, about some mean, is relatively small. This design approach possibly allows the elimination of the secondary mirror adjust mechanism thereby saving weight and reducing telescope complexity. Our "LUTE Primary Mirror Materials and Design Study Report", PR D15-0013A, discusses additional aspects of this design and includes a schematic of how this design approach could be implemented.

Based on the weight allocation of 84 kg for the telescope assembly, we concluded that the material of choice for LUTE is beryllium. This being the case, we calculated the amount of PM-to-SM despace if we assumed an all beryllium telescope and a telescope assembly temperature of 293 K (i.e. room temperature). These calculations also assumed that the mean temperature of the operational LUTE is 160 K with a range of temperature about this mean of ± 100 K. We used the data included in PR D15-0013A to account for CTE as a function of temperature. The calculations are as follows using the primary mirror as the reference.

- Beryllium structure:

$$(\Delta L)\text{ mean-to-cold} = \{(\Delta L)\text{ for 160K - 60 K}\} = 130\ \mu m$$

$$(\Delta L)\text{ mean-to-hot} = \{(\Delta L)\text{ for 160K - 260 K}\} = 487\ \mu m$$

Therefore for beryllium, the worst case is for the mean-to-hot case when the PM-to-SM spacing "grows" by 487 µm. However for a telescope which uses the same material throughout its optical "train", the telescope is athermalized. What is implies is that even though the spacing has changes by 487 µm, the radius of curvature of the primary and secondary mirror has changes by the same ratio. Therefore by definition, the wavefront error is identically zero (of course due to material inhomogeneities it is not identically zero.)

When we considered the metering bar approach several issues were immediately evident. First was that the temperature "swings" of the telescope is measured in "100's" of degrees not "a few degrees" which we typically would anticipate when considering a metering bar design and secondly, the optics are beryllium, not the more conventional "glass" optics where radius of curvature matching with "glass" metering rods could be accomplished. As a example of why a metering rod approach is not appropriate for LUTE, we continue similar calculations as shown above.

- Fused quartz metering rods:

$$(\Delta L) \text{ mean-to-cold} = \{(\Delta L) \text{ for } 160K - 60\ K\} = 36\ \mu m$$

$$(\Delta L) \text{ mean-to-hot} = \{(\Delta L) \text{ for } 160K - 260\ K\} = 13\ \mu m$$

These calculations show that even though the relative motion between the mirrors is much less, this motion obviously does not match the corresponding radius of curvature changes that the beryllium mirrors undergo. If the mirrors were fabricated from fused quartz (it is our opinion that this could only happen if the telescope weight allocation of 84 kg was significantly relaxed), then an assessment of the wavefront errors caused by the uncertainty of these values (remember material inhomogeneities, etc.) would need to be undertaken.

We made similar calculations to assess the impact of axial (i.e. along the telescope's length) temperature gradients on telescope performance. In this case, a telescope which uses the same material for both the structure and the optics does not necessarily enjoy any benefit when considering thermally induced deformations. This is shown in the Table 4-1 were we calculated allowable telescope axial temperature gradients to meet the PM-to-SM alignment requirement of 0.0212 waves rms (@ 0.6328 µm) due to lunar day-to-night changes as shown in PR D15-0013A. These results show that for axial temperature gradients, the all beryllium telescope will require a focus mechanism based on our understanding of the thermal analysis results presented in the MSFC report which suggests that the telescope axial gradients will be in excess of the 0.3K allowed. Conversely, a large benefit would be realized if the fused quartz metering bar design was chosen based on the allowable axial gradient. However as discussed, the PM-to-SM separation due to bulk temperature results clearly shows that LUTE is not suitable for the metering bar approach.

We did not conduct a LUTE-specific optical sensitivity analysis. In lieu of this we scaled sensitivity results from a similar three mirror telescope design. These sensitivities are shown in Table 4-2. We recommend that further work be undertaken to determine the specific optical sensitivities and that further analysis on PM-to-SM decenter (i.e. motion perpendicular to the optical axis) and relative tilts between the two elements be considered when bounding the allowable temperature gradients. From the results presented above we believe our inverted tripod design approach for the LUTE metering structure is appropriate.

TABLE 4-1
A MATERIAL WITH A LOW CTE OVER THE ENTIRE OPERATING TEMPERATURE RANGE IS PREFERRED SO THAT WAVEFRONT DISTORTIONS CAUSED BY TELESCOPE AXIAL TEMPERATURE GRADIENTS ARE MINIMIZED

Operating Temp (K)	Allowable Axial Temp Gradient (K) Beryllium	Fused Quartz
260	0.3	30
160	—	—
60	1.5	4

TABLE 4-2
SCALED RESULTS FROM A SIMILAR OPTICAL DESIGN WERE USED TO CALCULATE ALLOWABLE TELESCOPE AXIAL TEMPERATURE GRADIENTS

Secondary Mirror Motion	Wavefront Distortion Sensitivity (waves rms @ 0.6328 µm)
• 1 µm despace	0.02
• 1 µm decenter	0.004
• 1 arcsec tilt	0.017

4.2 SECONDARY MIRROR FOCUS MECHANISM RANGE

To assess the precise amount of despace motion which the telescope must accommodate, a number of analyses and/or tests must first be conducted. These include:

a) LUTE-specific wavefront error sensitivity analyses
b) Metering structure material ΔL/L characteristics:
   1) uncertainty
   2) repeatability
   3) homogeneity
c) Assembly misalignments
d) Launch induced misalignment
e) Exact operational bulk and temperature gradients
f) 5/6's g release

We have attempted to begin this assessment assuming an all beryllium telescope which is aligned and tested in 1g at 293 K. These results are shown in Table 4-3. These values should be considered as a preliminary assessment which will need to be updated as the LUTE specific "architecture" in terms of structural form and material choice is baselined.

One must apply considerable margin to account for the error sources shown in Table 4-3 which are "tbd." We believe the LUTE secondary mirror mechanism should have a minimum despace range of ±1 mm. For reference, the HST SM mechanism has a despace range of approximately ±3 mm.

TABLE 4-3
IDENTIFICATION OF DESPACE ERROR SOURCES HAVE BEEN MADE. ADDITIONAL ANALYSES AND TEST DATA REQUIRED TO FULLY QUANTIFY THESE EFFECTS ON OPTICAL PERFORMANCE

Despace Error Source	Estimated Despace Motion (μm)	Equiv. Defocus Error (waves-rms)
• Initial misalignment	0.4	0.008
• 5/6 g release uncertainty	0.3	0.006
• Launch residual	tbd	tbd
• Bulk temp. effects		
- 260 K to 160 K	490	0
- 160 K to 60 K	130	0
• Temp. gradients		
- PM, SM, TM	tbd	tbd
- Metering structure	tbd	tbd
• ΔL/L effects		
- PM, SM, TM	tbd	tbd
- Metering structure	tbd	tbd

SECTION 5

MECHANICAL LAYOUTS

5.1 OVERALL UTVA

Our recommended LUTE telescope design described in detail in Section 3 is based on a set of requirements which dictates that the telescope have diffraction limited performance while at the same time be light weight and structurally stiff. Shown earlier in Figure 3-2, the isometric view of our telescope highlights the major telescope components which we believe will meet this set of requirements.

Figure 5-1 is an "exploded" view of the telescope providing further definition of its components, the material which the component is fabricated from, insight into the fabrication technique which we recommend for its construction, and other pertinent information to help in the overall understanding of form and function. Figures 5-2 and 5-3 provide the more classical "side" and "top" views of the telescope. These figures are "to scale" to show that all components are consistent with volume constraints and that no interferences occur which could jeopardize the overall telescope architecture.

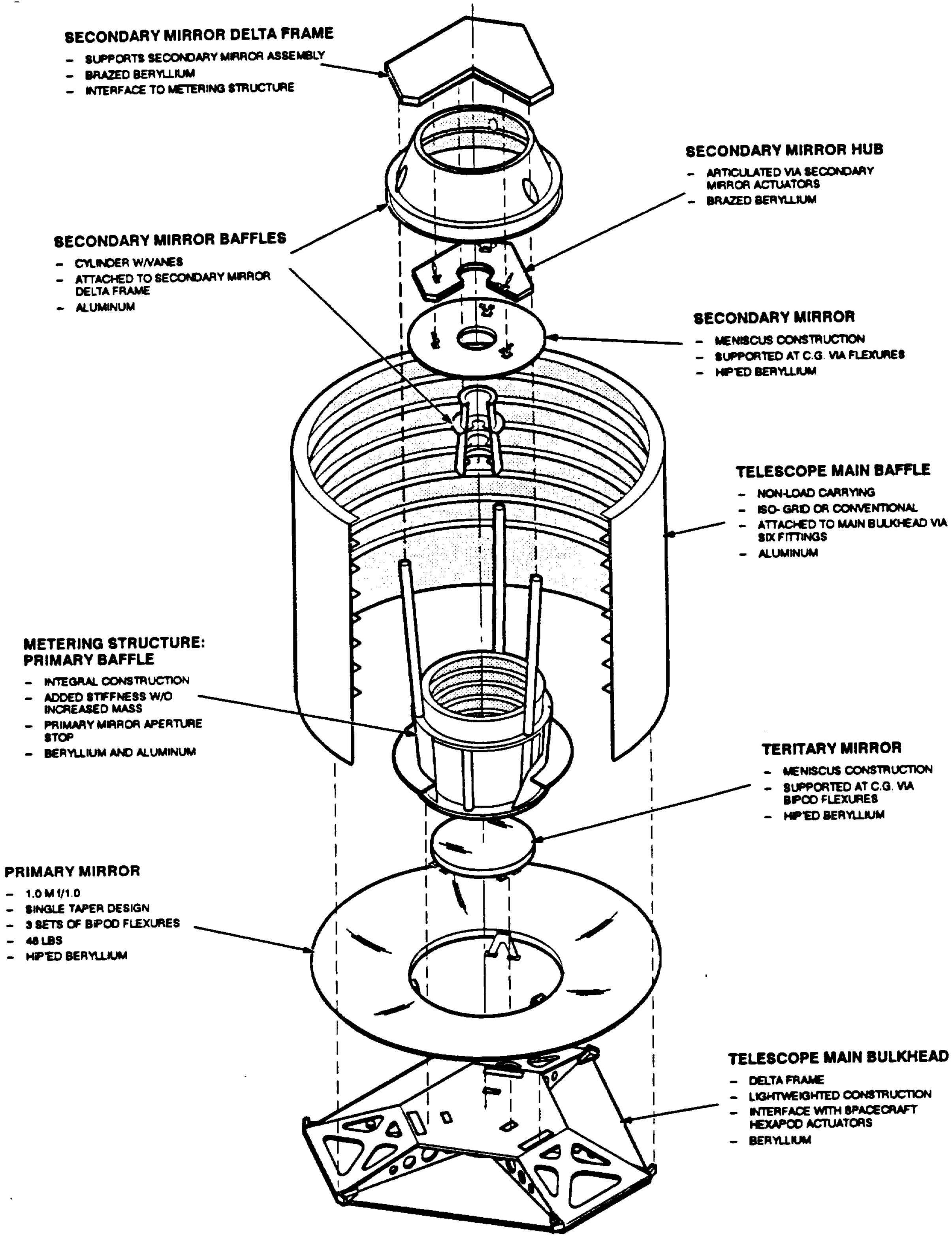


Figure 5-1. The "Exploded" View of the Lute Telescope Provide Insight into Assembly Sequences along with Material and Fabrication Techniques.

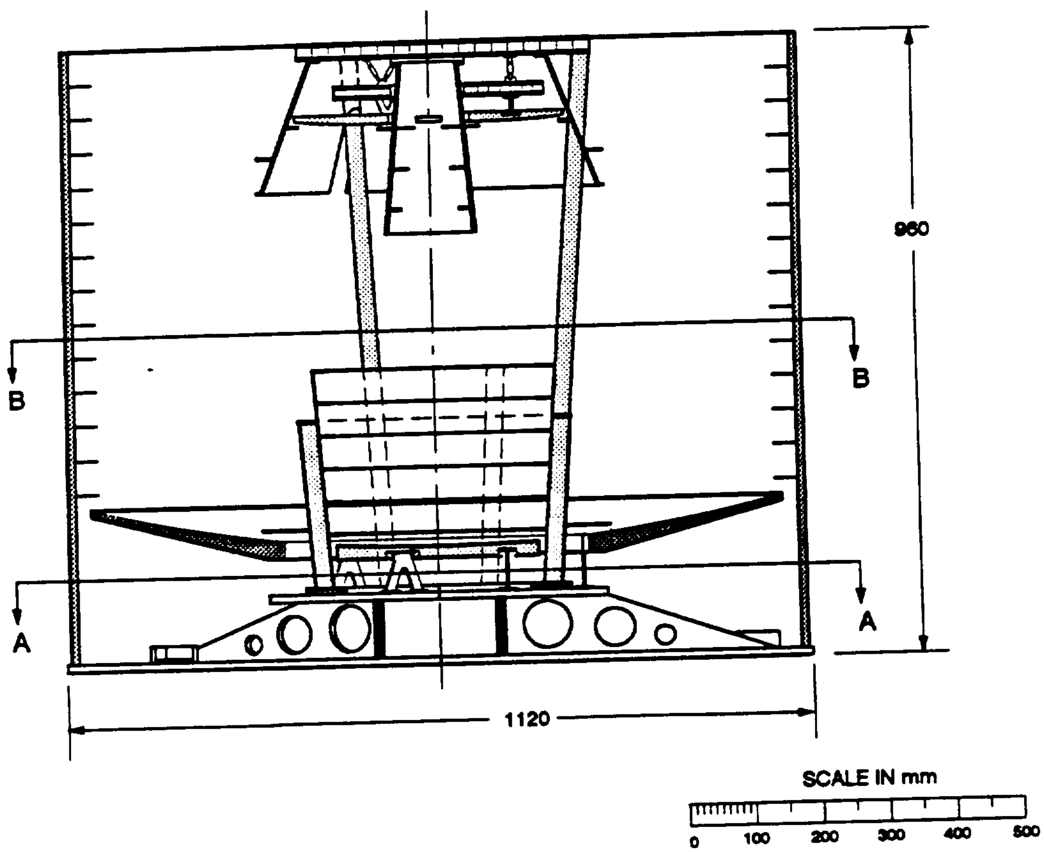
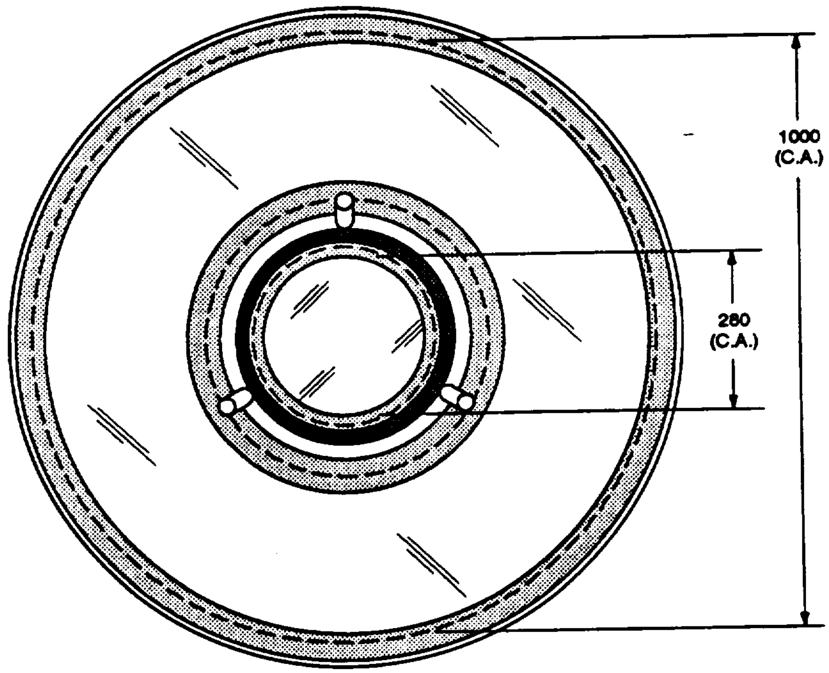
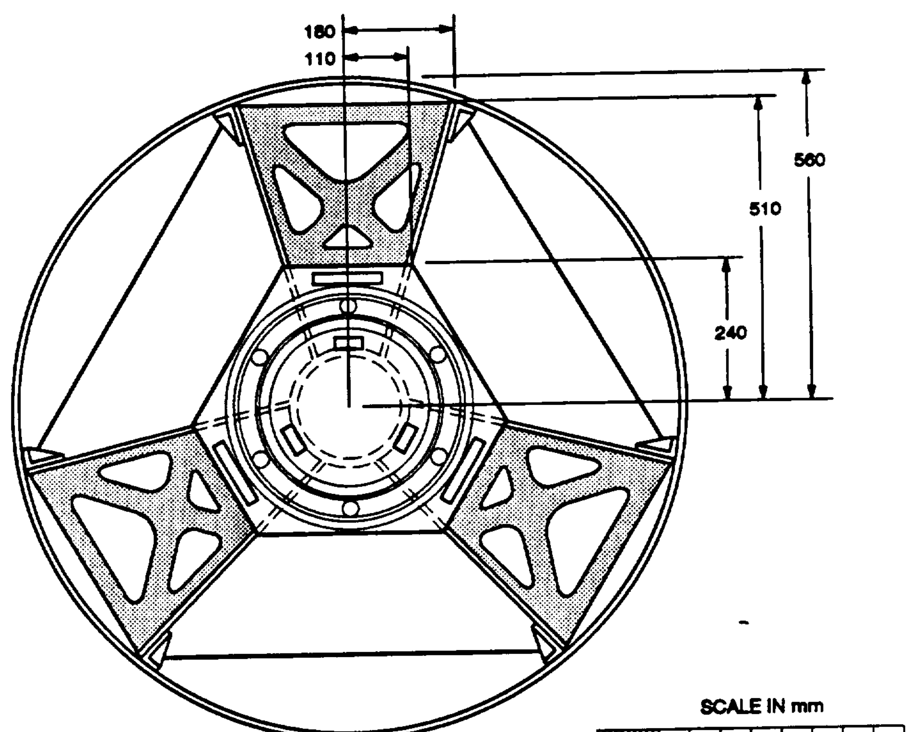


Figure 5-2. "Side" View of the Lute Telescope.



SECTION B–B



SECTION A–A

Figure 5-3. "Top Views of the Lute Telescope Sections "A-A" and "B-B" Highlights the Main Bulkhead and Primary/Tertiary Mirrors, Respectively.

SECTION 6

RECOMMENDATIONS

Our current investigation of the feasibility of the LUTE telescope substantiates the conclusions from our pervious LUTE study. That is, no areas have been identified that would indicate that the LUTE mission is not feasible. However, development of an ultra-lightweight, 1-m class telescope with visible wavelength diffraction-limited performance for operation across a temperature range of 60 - 260 K would undoubtedly prove to be very difficult. Following are some additional tasks and/or tests which warrant attention in the overall development of the telescope sub-system.

1) Use of other launch/lander vehicles could impact the conclusions made in our LUTE studies. A revisit of these studies is warranted if allowable telescope mass is significantly increased from 84 kg.

2) Sub-scale material testing of beryllium to quantify homogeneity as a function of location. Fabricate a full scale primary mirror blank, remove small sections and conduct CTE measurements as a function of temperature. Repeat these tests several times to extract repeatability data. Literature searches along with obtaining vendor information would complement this task.

3) Design and fabricate a brassboard (i.e. non-flight unit) of the LUTE telescope to investigate:

   a) thermally induced deformations of the telescope sub-system over the anticipated operating temperature range.
   b) simulate lunar "dust" applied to the telescope optical surfaces and correlate encircled energy degradation as a function of dust "buildup" with optical performance modeling.

4) Topics included in our previous study report:

   a) UV scatter measurements on small (3-5 cm diameter) polished and coated beryllium mirrors.
   b) Analysis of the candidate PM materials to identify the optimum temperature range for each material to achieve its optimum wavefront performance.
   c) Conduct optical analyses to:
      - support a re-evaluation of the existing wavefront error allocation to check its suitability for a UV telescope.
      - determine mirror alignment sensitivities in support of the concept to fabricate the TM on the same substrate as the PM.

APPENDIX A

LUTE VIEWGRAPHS FROM 4 MAY 1993 TECHNICAL TELECON

Lunar Ultraviolet Transit Experiment Study

Technical Telecon

Greg Ruthven
Mark Stier

4 May 1993

Agenda

- Objective
- Study Logic
- Telescope Configuration Description
- Performance Results
- Summary

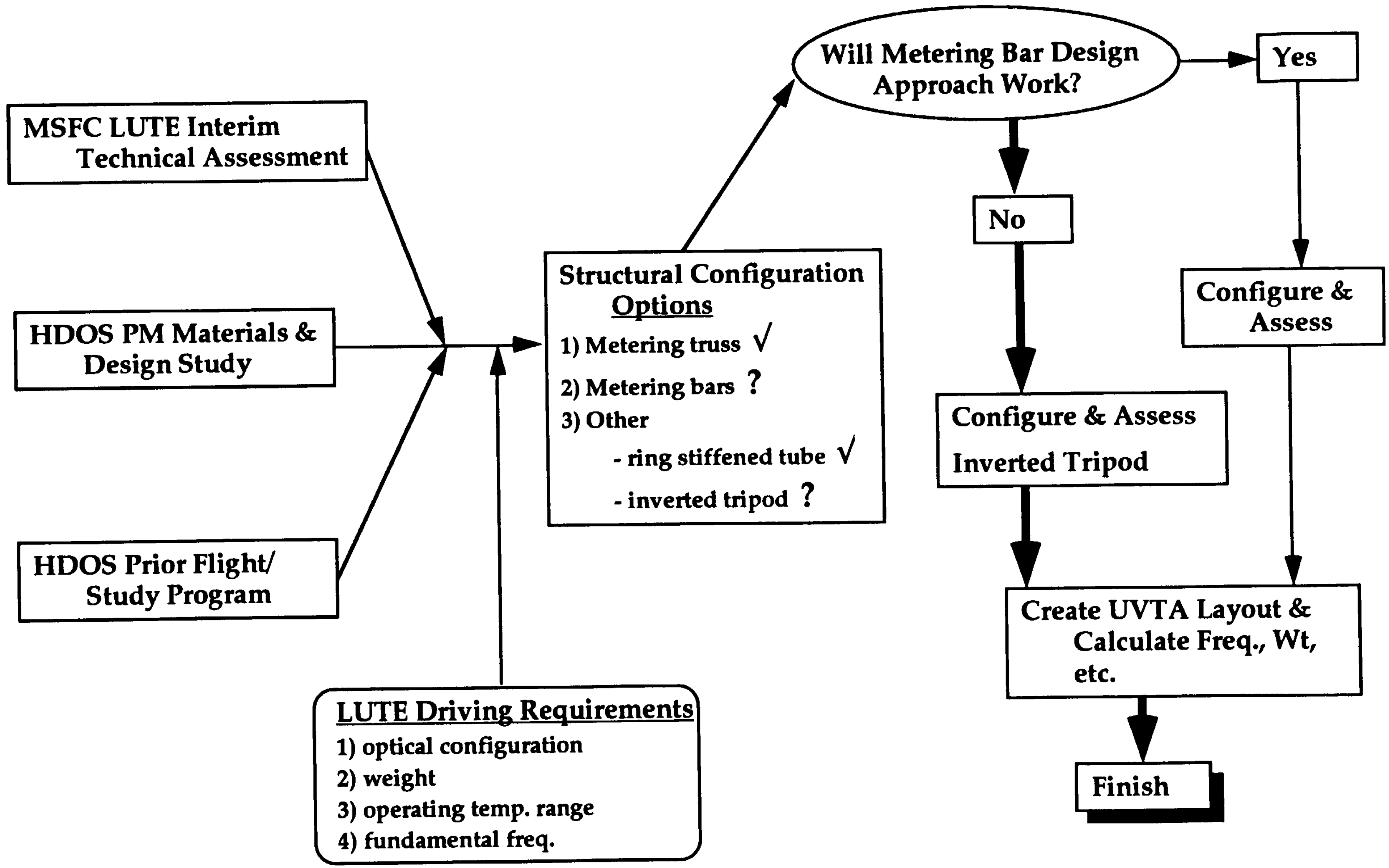
Objective

- **Conceptualize LUTE UVTA mechanical/structural architecture and assess its feasibility**

Present results showing:

1) Overall configuration
2) Weight estimates
3) Fundamental frequency
4) Maximum stress levels
5) Secondary mirror focus range

Study Logic

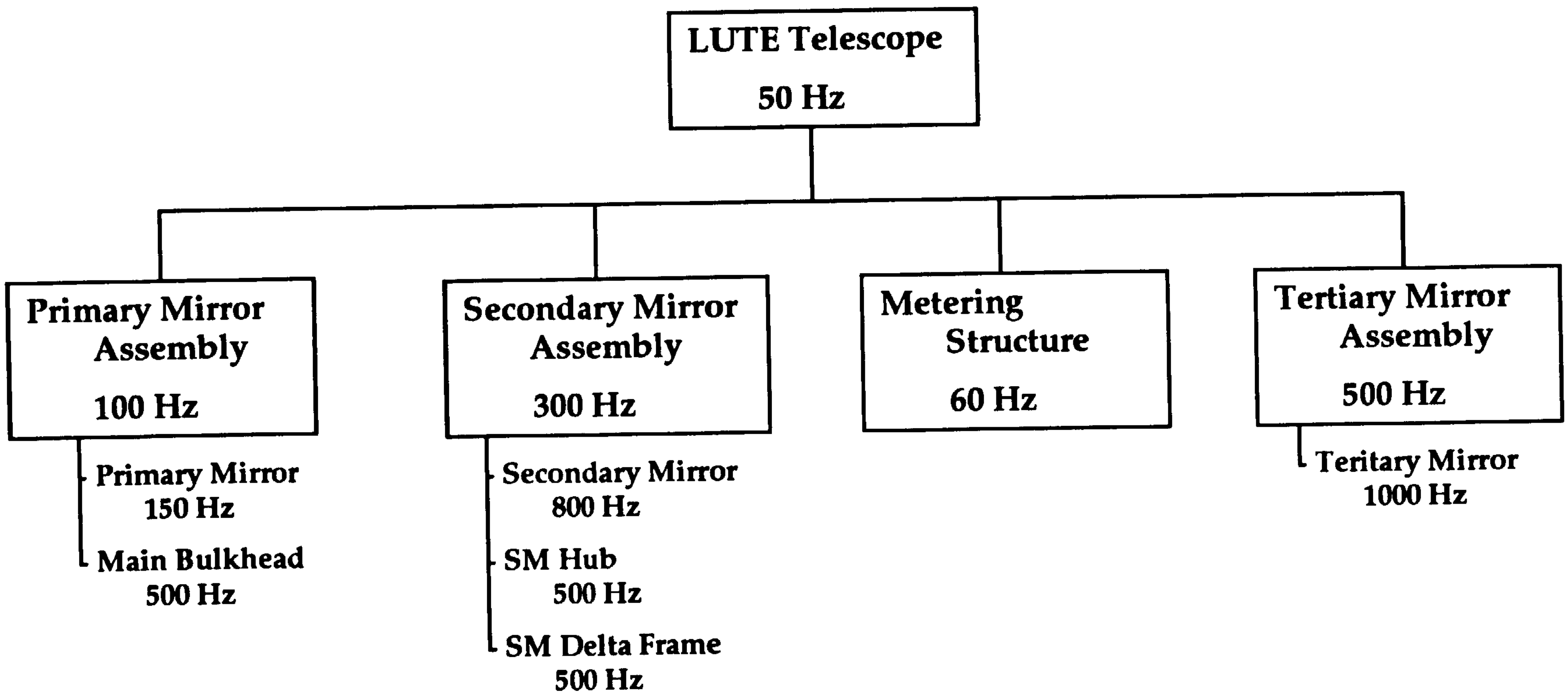

MSFC LUTE Interim Technical Assessment
HDOS PM Materials & Design Study
HDOS Prior Flight/ Study Program
LUTE Driving Requirements
1) optical configuration
2) weight
3) operating temp. range
4) fundamental freq.
Structural Configuration Options
1) Metering truss √
2) Metering bars ?
3) Other
- ring stiffened tube √
- inverted tripod ?
Will Metering Bar Design Approach Work?
Yes
No
Configure & Assess
Configure & Assess Inverted Tripod
Create UVTA Layout & Calculate Freq., Wt, etc.
Finish

Requirements

Item	Requirement	Comments
• Optical Design	• 3 mirror telesope • Diffraction limited @ 0.63 μm • 1 meter diameter • Operating wavelength: 0.1 to 0.35 μm	• Baseline MSFC design
• Weight	• Max. telescope weight: 84 kg	• Includes 18 % contingency
• Operating Temp Range	• 260 K to 60 K	• Nominal temperature range
• Fundamental Freq.	• >50 Hz (Telescope) • > 150 (Primary Mirror)	• Based on other programs

Fundamental Frequency Allocations

- Allocations based on two criteria:
  - Springs in series: • $K_{(eff)} = 1/\{1/K_{(1)} + 1/K_{(2)} + 1/K_{(n)}\}$
  - Ground testing: • Major resonances sufficiently separated for diagonosing test anomolies



Optical Sensitivities & Wavefront Error Budget

- **WFE estimates scaled from similiar optical designs**

Sensitivity	WFE (@ 0.6328 μm)
• 1 μm of SM despace →	0.02 waves rms
• 1 μm of SM decenter →	0.004 waves rms
• 0.01 deg of SM tilt →	0.6 waves rms

units are:

waves rms, 1 wave = 0.6328 μm

- 0.0500 LUTE On–Axis Wavefront Error Allocation
  - 0.0335 Primary Mirror
    - 0.0184 Fabrication
      - 0.0154 Full Aperture
      - 0.0082 Sub–Aperture
      - 0.0058 Micro–Roughness
        - 0.0034 Measurement
        - 0.0034 Substrate
        - 0.0034 Coating
    - 0.0198 Fabrication to Moon Changes
      - 0.0063 Correction of Radius Error
      - 0.0188 Figure Errors
        - 0.0064 Flight Mount
        - 0.0168 Thermal Ground–to–Moon
    - 0.0198 Lunar Day–Night Changes
      - 0.0140 Thermal Radius Change
      - 0.0140 Thermal Figure Change
        - 0.0125 CTE gradients
        - 0.0063 T gradients
  - 0.0224 Secondary Mirror
  - 0.0158 Tertiary Mirror
  - 0.0224 PM, SM, and TM Alignment
    - 0.0071 Initial Alignment
    - 0.0212 Lunar Day–to–Night Changes
  - 0.0100 Measurement of On–Axis Wavefront
  - 0.0050 Alignment of SI

Metering Bar Design Approach

- **Metering bar design option assessed for thermal effects:**

Advantages:
1) Elimination of focus mechanism possible
2) Allows use of beryllium main support structure
3) Low CTE material for metering bars maintain despace.
4) Decenter control via axial & tangential flexures

Disadvantges:
1) May only be suitable for Δ(CTE) & temperature gradients

Example: Assume fused quartz metering rods; investigate despace:

- **Bulk temperature effects:**

(ΔL) mean-to-cold = {(ΔL) for 160 K - 60 K} = 36 μm, but requires 130 μm for Be mirrors
(ΔL) mean-to-hot = {(ΔL) for 160 K - 260 K} = 13 μm, but requires 487 μm for Be mirrors

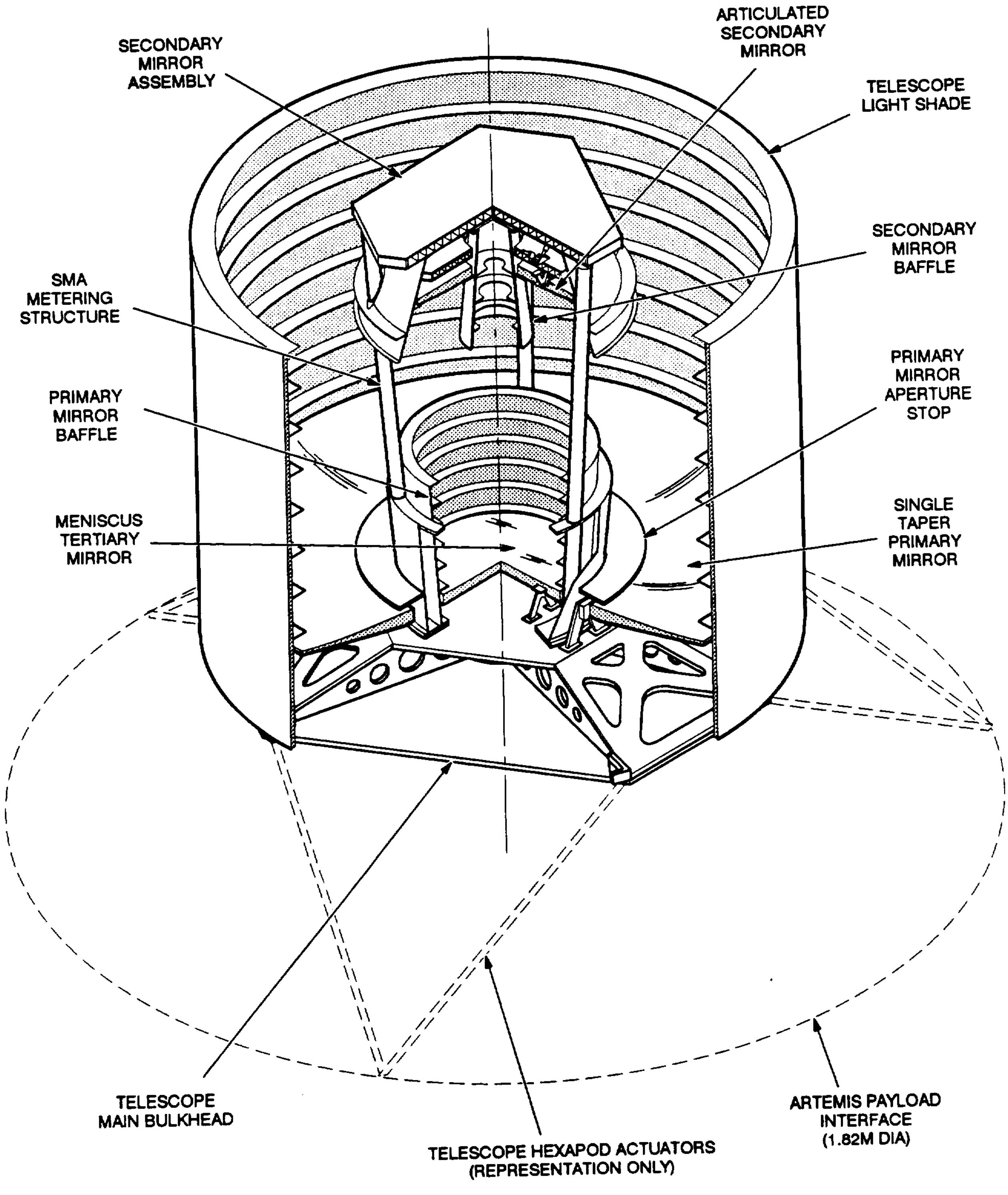
Therefore, required focus mechanism range (worst) = 487 μm - 13 μm ~ 0.5 mm

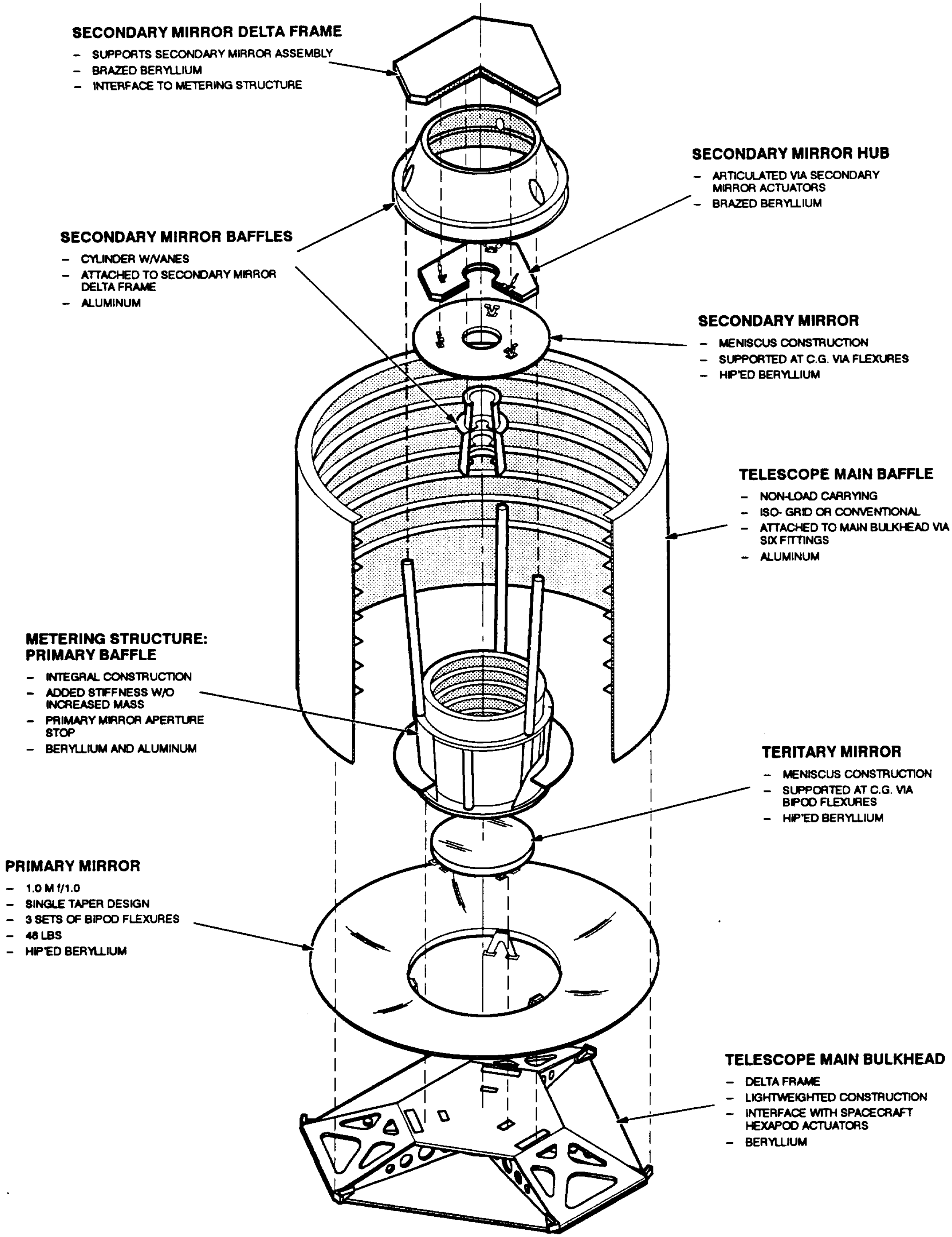
- **Axial temperature gradients effects:**

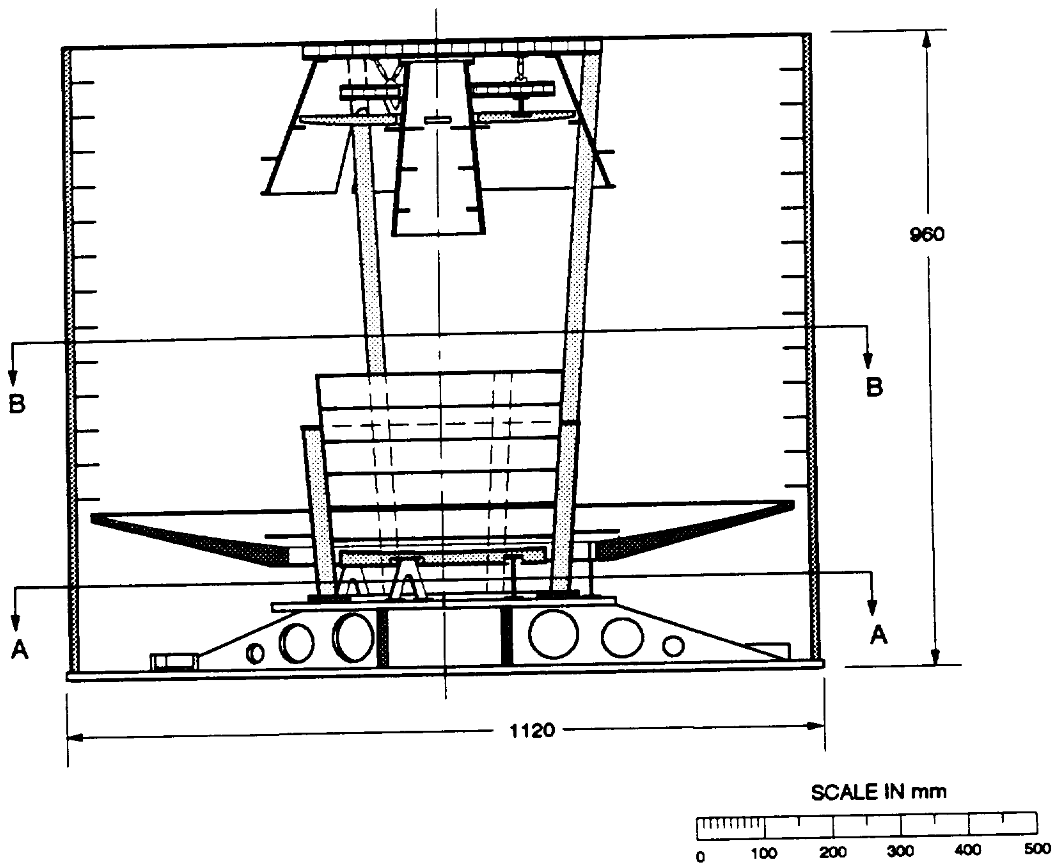
Allowed temp gradient @ 260 K = 30 K (F.Q.) vs. 0.3 K (Be)
@ 60 K = 4 K (F.Q.) vs 1.5 k (Be)

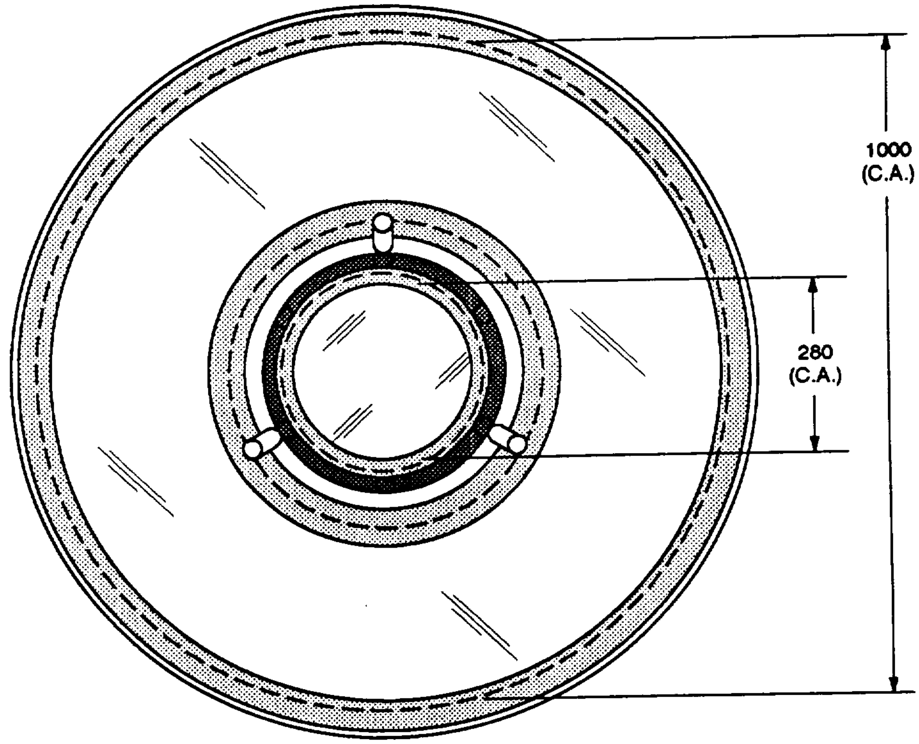
{Sensitivity(first order): 1μm (despace) = 0.02 waves rms WFE (bugeted value)}

Even an all beryllium telescope requires focus mechanism if axial temperature gradient exceeds 0.3 K

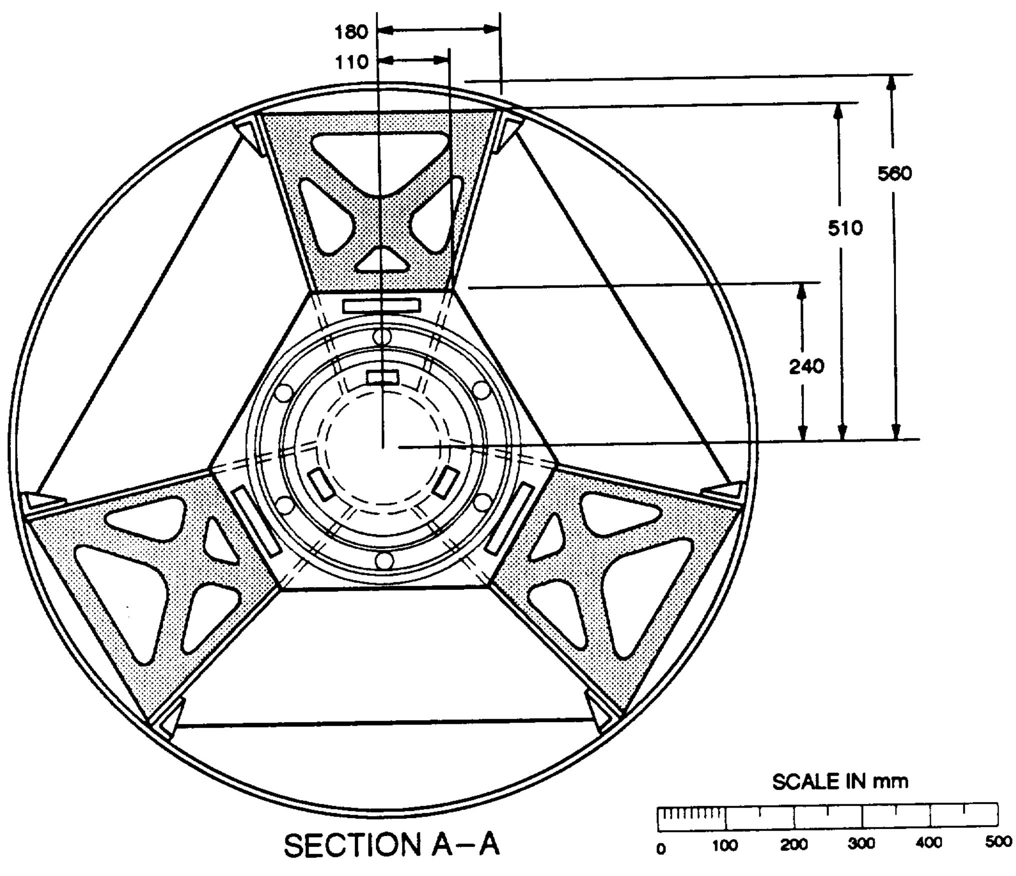

SECONDARY MIRROR ASSEMBLY
ARTICULATED SECONDARY MIRROR
TELESCOPE LIGHT SHADE
SECONDARY MIRROR BAFFLE
SMA METERING STRUCTURE
PRIMARY MIRROR BAFFLE
PRIMARY MIRROR APERTURE STOP
MENISCUS TERTIARY MIRROR
SINGLE TAPER PRIMARY MIRROR
TELESCOPE MAIN BULKHEAD
ARTEMIS PAYLOAD INTERFACE (1.82M DIA)
TELESCOPE HEXAPOD ACTUATORS (REPRESENTATION ONLY)


SECONDARY MIRROR DELTA FRAME
- SUPPORTS SECONDARY MIRROR ASSEMBLY
- BRAZED BERYLLIUM
- INTERFACE TO METERING STRUCTURE
SECONDARY MIRROR HUB
- ARTICULATED VIA SECONDARY MIRROR ACTUATORS
- BRAZED BERYLLIUM
SECONDARY MIRROR BAFFLES
- CYLINDER W/VANES
- ATTACHED TO SECONDARY MIRROR DELTA FRAME
- ALUMINUM
SECONDARY MIRROR
- MENISCUS CONSTRUCTION
- SUPPORTED AT C.G. VIA FLEXURES
- HIP'ED BERYLLIUM
TELESCOPE MAIN BAFFLE
- NON-LOAD CARRYING
- ISO- GRID OR CONVENTIONAL
- ATTACHED TO MAIN BULKHEAD VIA SIX FITTINGS
- ALUMINUM
METERING STRUCTURE: PRIMARY BAFFLE
- INTEGRAL CONSTRUCTION
- ADDED STIFFNESS W/O INCREASED MASS
- PRIMARY MIRROR APERTURE STOP
- BERYLLIUM AND ALUMINUM
TERITARY MIRROR
- MENISCUS CONSTRUCTION
- SUPPORTED AT C.G. VIA BIPOD FLEXURES
- HIP'ED BERYLLIUM
PRIMARY MIRROR
- 1.0 M f/1.0
- SINGLE TAPER DESIGN
- 3 SETS OF BIPOD FLEXURES
- 48 LBS
- HIP'ED BERYLLIUM
TELESCOPE MAIN BULKHEAD
- DELTA FRAME
- LIGHTWEIGHTED CONSTRUCTION
- INTERFACE WITH SPACECRAFT HEXAPOD ACTUATORS
- BERYLLIUM

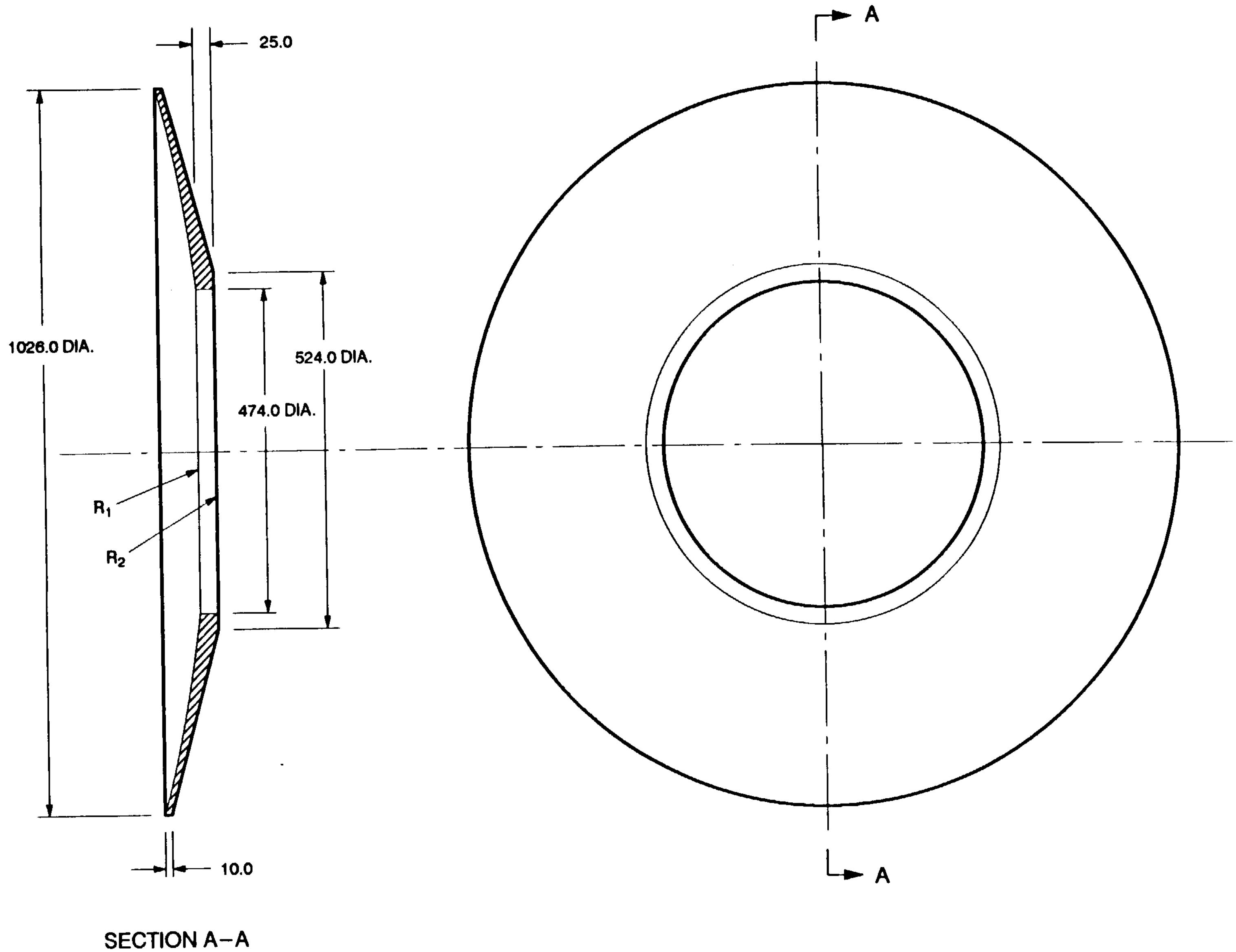

960
B
B
A
A
1120
SCALE IN mm
0
100
200
300
400
500



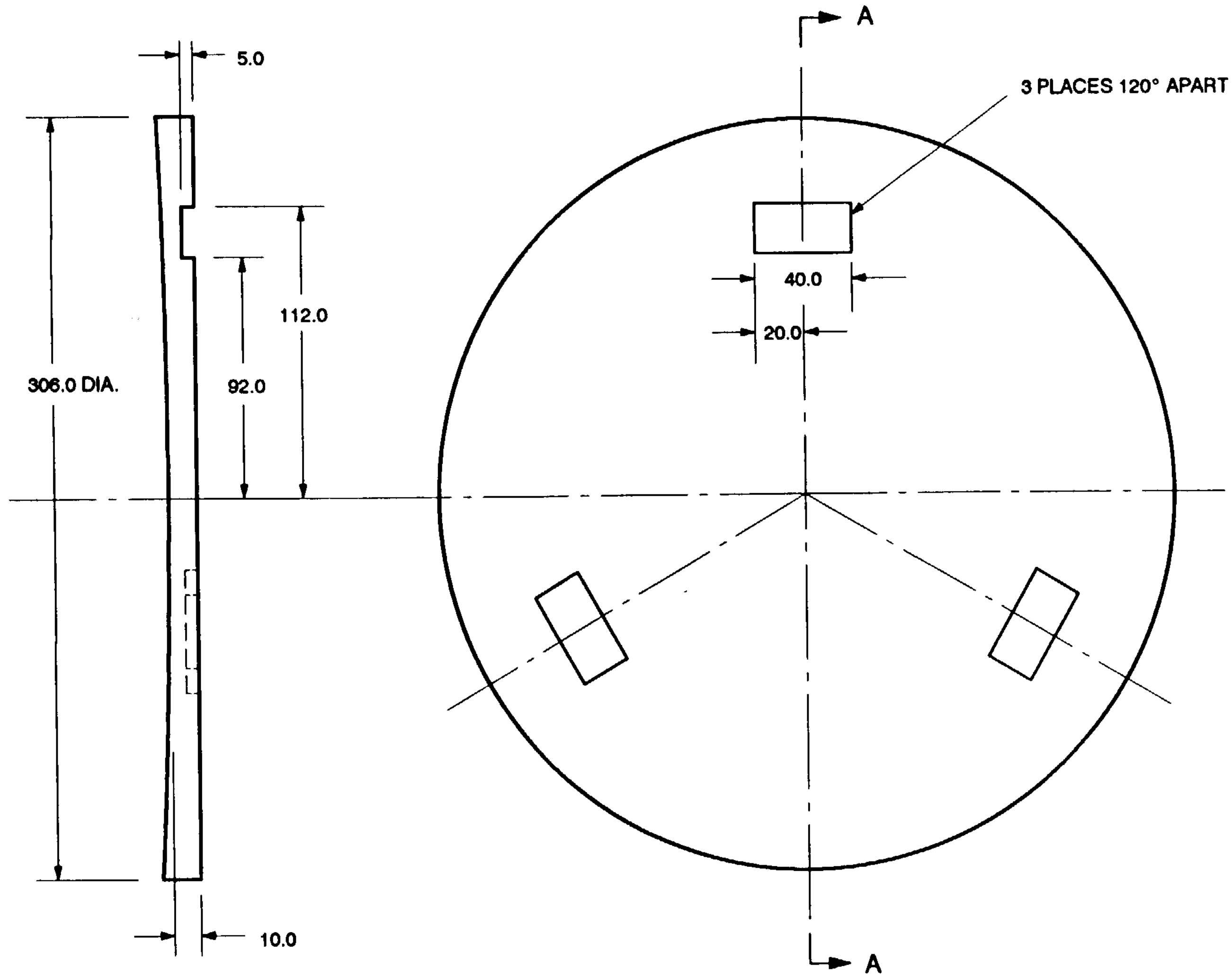
SECTION B–B



SECTION A–A



1.03 METER f/1.0 LUTE PRIMARY MIRROR



SECTION A–A

0.3 METER f/0.6 LUTE TERTIARY MIRROR

Inverted Tripod Design Approach

- **Question:** Can we use the conclusions from the "PM Materials & Design Study" to help configure the UTVA structural architecture?

- **Answer:** Yes...........but it wasn't obvious at first !!!!

The Driver: PM leading candidate geometry is a "single arch" mounted @ its inner rim.

- Can HDOS fabricate an integral PM/TM?

Yes.................but, from the current study results.................

Separate mirrors are preferred..........

Why?
- Weight penalty for integral PM/TM = 10 lbs; but more importantly.......
- Take advantage of the geometry to configure the telescope

Why? Significant weight savings for separate PM/TM design apparoach in areas of:

1) Main Bulkhead

2) Main Baffle

Weight Estimate (1)

- Current study concentrated on "structural" weight (i.e. main baffle, metering structure, etc)

  - one-for-one comparison desired (allocation vs estimate)

  - thermal control, electronics, SM actuators still considered allocations

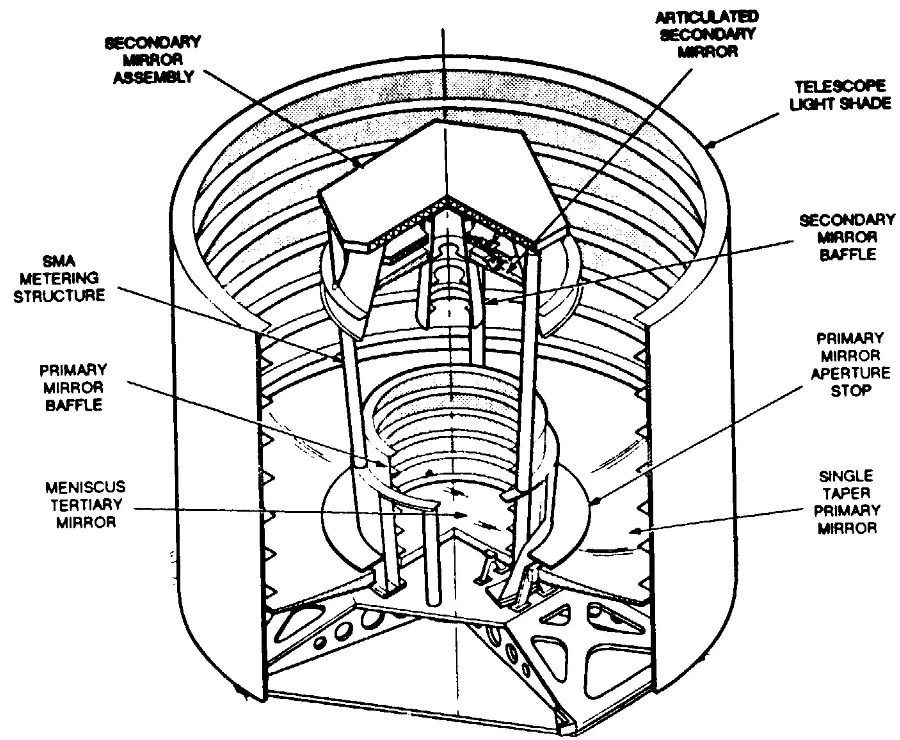
		LUTE OBSERVATORY Weight Estimate			
Major Element	Sub-Ass'y/Component	Weight Allocations (lbs)	(kg)	Weight Estimate (lbs)	(kg)
1) Mirrors					
	- Primary Mirror	48	21.8	48	21.8
	- Secondary Mirror	6	2.7	6	2.7
	- Tertiary Mirror	3	1.4	3	1.4
	Sub-Total:	57	25.9	57	25.9
2) Structure	Baffle Sub-Ass'y				
	- Main	9	4.1	13.0	5.9
	- Central	2	0.9	2.0	0.9
	- SM	1	0.5	4.6	2.1
	Sub-Total:	12	5.5	19.6	8.9
	Mirror Mounts				
	- PM	5	2.3	2.0	0.9
	- SM	3	1.4	1.5	0.7
	- TM	2	0.9	1.5	0.7
	Sub-Total:	10	4.5	5	2.3
	Main Bulkhead Sub-Ass'y				
	- Main bulkhead	12	5.5	14.9	6.8
	- S/C interface fittings (3)	3	1.4	3	1.4
	Sub-Total:	15	6.8	18	8.1
	Metering Struc. Sub-Ass'y				
	- Metering struc bars (3)	3	1.4	3.4	1.5
	- Interface fittings (6)	3	1.4	1.5	0.7
	Sub-Total:	6	2.7	4.9	2.2
	SM Sub-Ass'y				
	- Spider	4	1.8	0	0.0
	- Spider ring (Delta frame)	3	1.4	2.8	1.3
	- SM hub	3	1.4	3.1	1.4
	- Spider flexures (3)	3	1.4	0	0.0
	- Actuators (6)	6	2.7	6	2.7
	- Cabling	4	1.8	4	1.8
	Sub-Total:	23	10.5	15.9	7.2

LUTE
Telescope Structural Design Study

Weight Estimate (2)

Hughes
Danbury Optical Systems

3) Electronics	• ACE		3	1.4	3	1.4
	• TCE		3	1.4	3	1.4
	• DMS		3	1.4	3	1.4
	• ASE		3	1.4	3	1.4
	Sub-Total:		**12**	**5.6**	**12**	**5.6**
4) Thermal Control	• Heaters		2	0.9	2	0.9
	• Thermocouples		2	0.9	2	0.9
	• MLI		3	1.4	3	1.4
	Sub-Total:		**7**	**3.2**	**7**	**3.2**
5) Alignment Sensor	• WF Sensor		10	4.5	10	4.5
	• Sensor mount		2	0.9	2	0.9
	Sub-Total:		**12**	**5.6**	**12**	**5.6**
	Total (w/o Reserve):		**164.0**	**70**	**151.3**	**69**
	Reserve:		**31.6**	**14**	**31.1**	**14**
	Total:		**185.6**	**84**	**182.4**	**83**



Fundamental Frequency Estimate

- Major components assessed via hand calculations & NASTRAN

Component:	Requirement	Calculated Value
• Primary Mirror Assembly		
- Primary Mirror	150 Hz	260 Hz
- Main Bulkhead	500	870
• Secondary Mirror Assembly		
- Secondary Mirror	800 Hz	1045
- SM Hub	500	800
- SM Delta Frame	500	725
• Metering Structure (w/ rigid SMA)	60Hz	65 Hz
• Teritary Mirror Assembly		
- Teritary Mirror	1000 Hz	1950 Hz
• Telescope Light Shade	200 Hz	242 Hz

Launch Induced Stresses

- **Telescope design is frequency driven........stress levels are low**
  - Hand calculations made of major components
  - Quasi-static limit load factor of 15 g's rms was assumed
  - F.O.S. of 1.25 & 1.5 for yield & ultimate used

Component:	Est. Max Stress Level (psi)	Margin of Safety	Nature
- Primary Mirror	2700	>1	Bending
- Main Bulkhead	5200	>1	Bending
- Secondary Mirror	6100	>1	Bending
- SM Hub	4000	>1	Bending
- Metering Structure	9200	>1	Tension
- Teritary Mirror	800	>1	Bending
- Main Baffle	250	>1	Bending

SM Focus Mechanism Range

- **Basic Assumptions:** 1) LUTE telescope aligned and tested in 1g @ 293 K
  2) Telescope structure & optics are beryllium

Despace Error Source Source	Estimated Despace Motion (μm)	Equiv. Defocus Error (waves-rms)
• Initial misalignment	0.4	0.008
• 5/6 g release uncertainity	0.3	0.006
• Launch residual	tbd	tbd
• 260 K to 160 K	490	0
• 160 K to 60 K	130	0
• Δ(CTE) and T grad. effects	tbd	tbd
- PM		
- SM		
- TM		

We are uncertain at this time the SM focus mechanism requirements, but "worst case" estimate (F.Q. metering bars) → ± 1mm range

Conclusions

- Updated weight calculations consistent with previous allocations

- Fundamental frequency req'mts met
  - component designs are frequency driven, not stress driven

- SM focus mechanism required

- Image quality degradation effects due to metering structure needs further study

- Telescope design driven by mass budget & ΔT
  - use of other launch/lander vehicle would have major impact