ITTT: a state-of-the-art ultra-lightweight all-Be telescope

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ABSTRACT

The Infrared Technology Testbed Telescope (ITTT) is a demonstration telescope meeting the needs of the SIRTF mission, It is a Ritchey-Cretien form designed for diffraction limited performance at 6.5 pm, at 5.5 K with an 85 cm. clear aperture. The mirror and system focal ratios are j/1.2 and j/1 2 respectively. This paper describes the design and fabrication of the efficient, ultra-lightweight, all-beryllium telescope. The design incorporates a central metering tower and single arch primary mirror to achieve a total telescope mass of less than 30 kg. Cryogenic testing of the primary mirror demonstrates the stability of the I-70-H (special) Be and the fabrication process. No thermal hysteresis was observed after repeated cycling to 5 K, and cryo-null figuring was utilized to overcome the small thermal instability observed at that temperature.

Keywords: infrared, telescope, cryogenic stability, beryllium, SIRTF, ultra-lightweight telescope, all-beryllium telescope, fabrication methods, mirrors

1. INTRODUCTION

A number of current and future NASA space science missions and mission studies have highlighted the infrared (≈1-20 μm) as the key spectral region for study of the early universe, observation of extra-solar planets, and characterization of atmospheres of extra-solar planets in a search for markers pointing to life. In order that the sensitivity of the observations not be limited by thermal emission from the observatory, it is necessary to cool the optics. The required operational temperature depends on the longest observing wavelength but is typically in the 5-70 K range. This requirement has a major impact on the mission architectures. There is also a strong desire to reduce the cost of future missions which leads to simplified designs, accelerated development, reduced development costs, reduced mass of the flight system and utilization of smaller launch vehicles. The combination of science goals, engineering considerations and programmatic limitations places some unique requirements on the optical system designs and technologies.

In 1990, the Jet Propulsion Laboratory (JPL) of the California Institute of Technology was assigned responsibility for the Space Infrared Telescope Facility (SIRTF) which is currently planned to launch in late 2001. SIRTF will be an ultra-lightweight, 85 cm aperture, infrared telescope, diffraction limited at 6.5 μm, cooled with liquid helium to <5 K and will perform imaging and spectroscopy in the 3.5 pm to ≈160 μm region of the spectrum, It will follow two previous and highly successful cryogenic infrared telescopes into space. The telescope for the Infrared Astronomical Satellite (IRAS)[1], launched by NASA in 1983, was a 70 kg, 57 cm aperture Richey-Chretien design, manufactured from vacuum hot pressed beryllium (Be) and operated at

$\approx$4 K. This telescope was diffraction limited at $\approx$20 µm. Twelve years later, in 1995, ESA launched the Infrared Space Observatory (1S0)[2] which is still in operation. The 1S0 telescope is also a Richey-Chretien design with a mass of 50 kg, a 60 cm aperture and an operating temperature of $\approx$4 K. The telescope structure is manufactured from invar and aluminum and the mirrors are lightweighted fused silica. It achieves diffraction limited performance at $\approx$5 µm, much better than IRAS.

Prior to 1990, the NASA Ames Research Center had the programmatic responsibility for SIRTF and conducted research on candidate cryogenic mirror designs. That work focused primarily on glass and Be mirror technology.[3-6] The conclusions of that work were that both glass and Be mirrors showed measurable cryogenic distortion when cooled to near liquid helium temperature but that when returned to room temperature the glass mirrors essentially returned to their original shape while the Be mirrors did not. The Be mirrors exhibited the now well known hysteresis effect. Further, the Ames researchers showed that, with a fused quartz mirror, the effects of the cryogenic distortion could be compensated for by a process now known as cryo-null figuring. The Ames researchers figured the fused quartz mirror at room temperature with the inverse of the measured cryogenic distortion such that when cooled, it achieved near diffraction limited performance. This technique had previously been successfully applied to the IRAS primary mirror'.

In early 1993, SIRTF underwent a major redesign that necessitated unprecedented levels of lightweighting in all areas including the telescope, which was allocated only 30kg. As a result, JPL embarked on a technology development program to demonstrate the viability of an ultra-lightweight, cryogenic telescope that had twice the collecting area of IRAS, half the mass and was diffraction limited at a substantially shorter wavelength (6.5 µm vs. 20 pm). The initial effort focused on the manufacturing and cryogenic testing of 0.5 m test mirrors fabricated from the two leading candidate mirror materials at that time – Be and reaction bonded silicon carbide. Glass designs were judged to be too heavy to achieve the mass goal.

New manufacturing processes were designed and implemented for the Be mirror with the intent to minimize internal stresses in the final part. In cryogenic optical tests at the NASA Ames Research Center, the 0.5 m Be mirror proved to be the most stable large Be mirror ever measured.[8] The thermal distortion from room temperature to 4.4 K was found to be comparable to that observed in most large fused silica mirrors. Even more importantly, there was no measurable hysteresis in the figure of the mirror as a result of thermal cycling.

The 0.5 m diameter silicon carbide test mirror was a closed back, lightweighted structure fabricated by United Technologies Optical Systems (UTOS) from reaction bonded optical (RBO) grade silicon carbide. Preliminary cryogenic optical testing of this mirror performed by Lockheed-Martin showed a small thermal distortion and a slight hysteresis upon return to room temperature[9]. There were plans to take the mirror to the Ames facility for further tests. However, when UTOS stopped producing the RBO silicon carbide optics, and this product was no longer available, those plans were dropped." The conclusion was that the silicon carbide mirror performance was comparable to that of the Be mirror and that on the basis of the subscale mirror evaluation program, both materials appeared to be viable candidates for cryogenic optical system applications.

In June of 1994, JPL issued the Infrared Telescope Technology Testbed (l'HIT) RFP inviting industry and academia to propose to design and build a demonstration telescope meeting the needs of the SIRTF mission. The principal requirements were that the ITTT should achieve diffraction limited performance at 6.5 μm, at 5.5 K with an **85** cm clear aperture and a total mass of <50 kg. The primary mirror and system focal ratios were specified as *f*/1.2 and *f*/12 respectively.

Hughes Danbury Optical Systems, Inc. (HDOS), Danbury, CT, was selected to build the ITTT based on their concept for a (nearly) all Be telescope utilizing a very mass efficient "central tower" design as shown in figure 1. The design is based on a single arch primary mirror attached to a lightweight bulkhead via three flexures. The secondary mirror is mounted in a similar fashion to the secondary mirror assembly. The secondary mirror assembly is attached to a lightweight metering tower that incorporates the primary and secondary cone baffles and three longitudinal struts into a single machined piece. The secondary mirror assembly is designed to accommodate a one degree of freedom focus mechanism. The total mass of the ITIT at completion is estimated to be 29 kg.

2. DESIGN

HDOS evaluated glass, Be and silicon carbide property and fabricability data in performing material trades. It was determined that the image quality requirement could be met in any of these three materials. To meet the image quality goal of 0.07 λ rms wavefront error (at λ = 6.5 μm) at 5.5 K, and simultaneously meet the telescope assembly mass goal of 30 kg was the real challenge. These goals could not be attained using a modified version of the IRAS telescope. A design was developed with a very lightweight primary mirror and central tower that combined the functions of metering structure, secondary mirror assembly mount, primary cone baffle and secondary cone baffle. Based on the properties listed in table 1 and preliminary estimates, it was clear that Be was the only material able to meet the weight and performance goals of the program.

Design trades then were conducted to minimize the mass of the primary mirror while still providing sufficient rigidity to meet the system structural and environmental requirements. A single arch design with a central hub mount was found to be most efficient, and the design shown in figure 2 then evolved. In this design, the primary mirror is supported on three biped flexures relatively close to the telescope axis. This allows the use of a relatively small diameter bulkhead, significantly reducing the mass of the bulkhead. A cross section of the primary mirror assembly is shown in figure 3. The bulkhead supports both the primary mirror and the metering structure that extends through the central hole of the primary mirror. The secondary mirror is attached to its

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* Another company has since purchased the rights to the UTOS process and has started fabrication of SiC mirror blanks as described later in this conference.

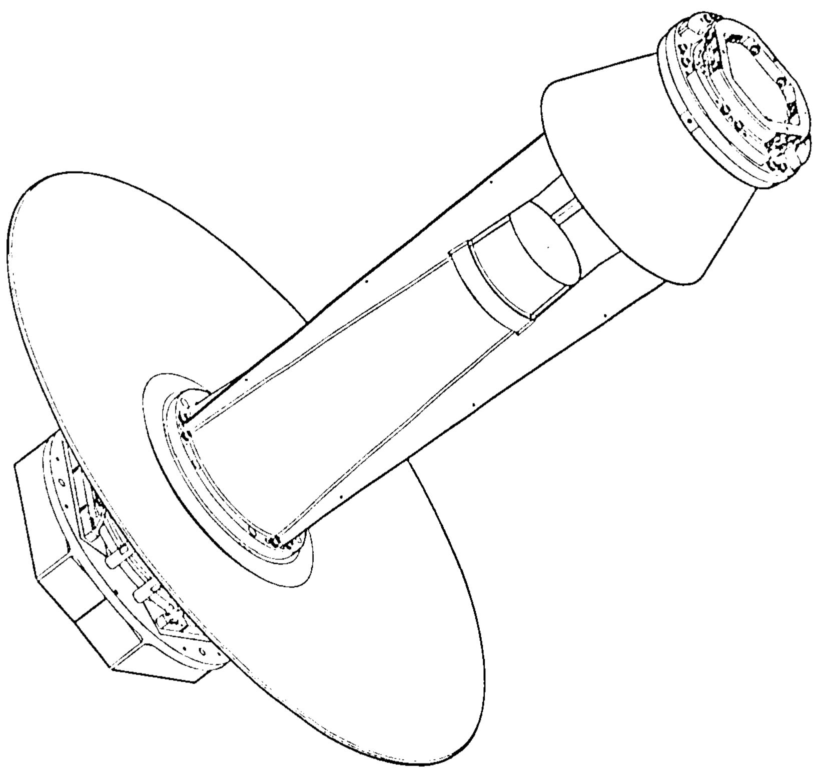

Figure 1. Isometric view of the Infrared Telescope Technology Testbed

Property	Beryllium		Reaction Bonded Silicon Carbide		Fused Quartz	
	10 K	293 K	10K	293 K	10 K	293 K
Coeff. Of thermal expansion, a (ppm/K)	0.001	11.3	0.015"	2.6	-0.26	0.50
Thermal conductivity, k (W/m K)	37	216	300"	155	0.11	1.4
Specific heat, Cp (W s/kg K)	0.39	1925	0.1*	670	4.0	750
Steady state distortion coef, a/k (μm/W)	((0.001	0.052	((0.001	0.017	2.4	0.36
Density, ρ (g/cm^3)	1.850		2.89		2.19	
Young's modulus, E (GPa)	287		330		74.5	
Self-deflective: equal mass, E/ρ^3 (arb.)	45		14		7	
Total contraction, 293K to 10K (ppm)	1298		350"		-50	
*Estimated						

Table 1. Properties of ITTT candidate materials showing that Be has the best combination of properties at 10 K and can be made 3x stiffer than SiC for the same telescope mass.

cell with three biped flexures, and the assembly is attached to three blades that arc an integral part of the central tower. The one piece central metering tower then provides the combined functions of primary and secondary baffles and spider, enables low mass by minimizing the diameter of the support structure, assures a geed thermal path to the secondary mirror, dramatically reduces the parts count in the telescope and has good stiffness/structural properties. The secondary mirror assembly is designed to accommodate a one degree of freedom focus mechanism but this element is not incorporated in the current hardware.

Since testing of the primary mirror assembly was to be performed prior to the completion of the balance of the telescope, the adapter tube was designed to be assembled with the primary mirror so that the central tower/secondary mirror assembly could later be attached as a unit and only a simple alignment would then be required. To accommodate testing in the JPL test facility an adapter plate was also designed, and the bulkhead mounts to the adapter plate with three biped flexures. Copper cooling straps are used to facilitate cooling during cryogenic testing.

The grade of Be chosen for the telescope is hot isostatically pressed I-70-H (special), identical to that used in the 0.5 m. test mirrors. All telescope components arc Be except for the six titanium biped flexures and several pins used to mount the primary and secondary mirrors.

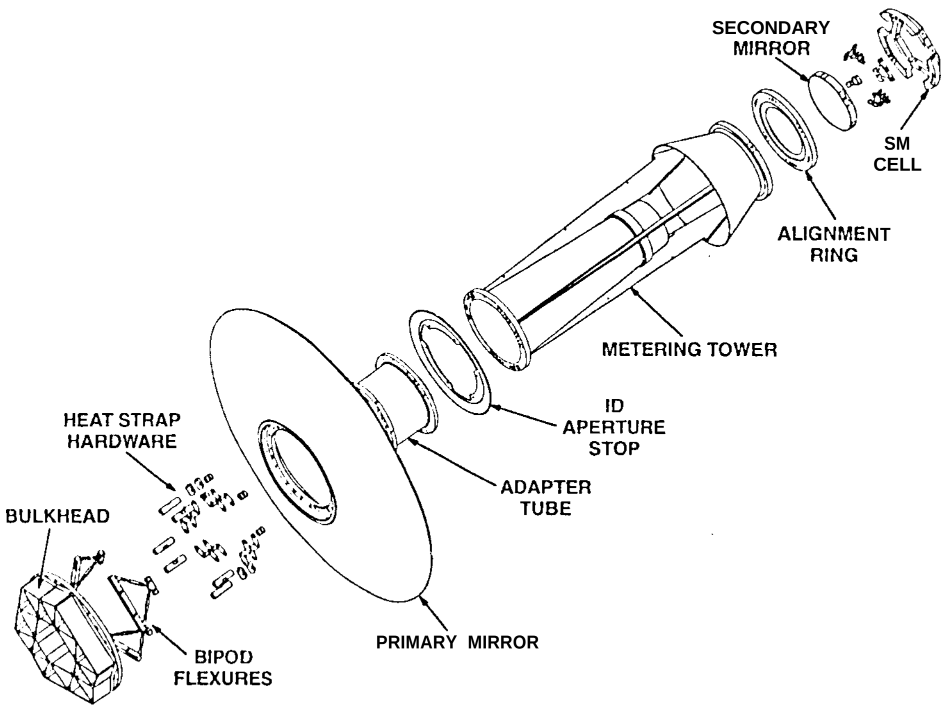

Figure 2. Exploded view of ITTT showing the simplicity of the design.

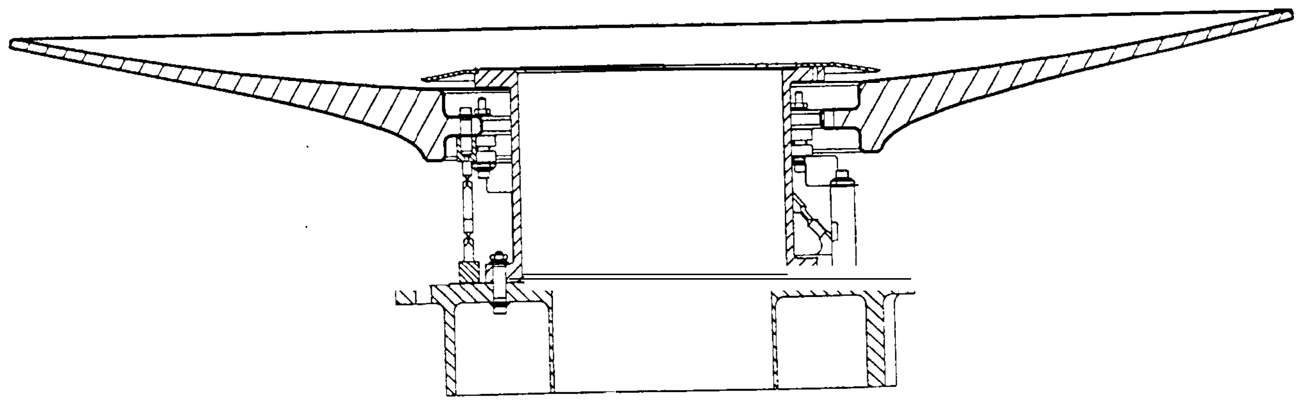

Figure 3. Cross-sectional drawing of the ITTT primary mirror assembly showing bulkhead, adapter tube, primary mirror and ID aperture stop with bipod flexures and connecting hardware.

The optical design, a Ritchey-Cretien, employs two hyperboloids with a primary aperture of 85 cm. The telescope has an effective focal length of 10.2 meters and an imaging bundle of *f*/12. The field of view is 26 arc minutes in diameter and the design operational bandwidth is 3 to 200 μm.

3. MANUFACTURING PLAN, FABRICATION& IN-PROCESS TESTING

A manufacturing plan was prepared that prescribed detailed fabrication steps from Be powder to finished optic. The emphasis was on eliminating possible sources of dimensional instability and closely followed the plan used for the earlier 0.5 m test mirrors. In summary, the manufacturing methodology was:

- Start with clean, fine grained, moderate to low oxide, impact ground 1-70 Be powder,
- Consolidate by HIP
- Use progressive machining for all steps,
- Acid etch after every machining and every rough grinding step,
- Anneal at 785° C after HIP and every rough machining step and
- Thermal cycle after the last machining step and after every grind and polish step.

All Be components for the telescope were fabricated from the same lot of 1-70 (special) powder, HIP'ed in three billets in the same HIP run.. One billet contained material for the two mirrors and seconcary mirror cell, one was for the central tower and the third contained the remainder of the components. HDOS used the same modified I-70 material and virtually the same manufacturing plan as was used for the 0.5 m mirror, but with more extensive stress relief steps because of the larger size and complexity of the components. I-70-H Be was chosen over other grades because of its polishability, relatively high strength and good stability, as shown for several mirrors fabricated during the past decade[5, 8, 10]. The use of spherical powder, while attractive for its potential superior thermal stability behavior, was not chosen due to the added risk for this relatively unknown Be grade.

The 1-70 powder was chemically cleaned and very tine particles were not used. The components were machined from cylindrical billets HIP'ed at 830° C and 103 MPa. To minimize risk no attempt was made to produce near-net-shape billets. Material properties exceeded the specification for I-70-H and are given in Table 2. The average grain size was 6.3 μm and the density was ≥100% of theoretical. Beryllium oxide content for the billets averaged 0.5 %

The billets were machined to rough shape at Brush Wellman, Elmore, OH.. Intermediate and final machining was performed at Lockheed-Martin American Beryllium Co., Tallevast, FL. During the machining processes, the mirror blanks were annealed twice and acid etched three times.

PROPERTY	Ultimate **Tensile Strength**	**Tensile Yield Strength**	**Microyield Strength**	**Elongation**	**Coeff.** of **Thermal Expansion**
Units	MPa	MPa	MPa	%	ppm/K
I-70-H Spec.	345	**207**	**21**	**2.0**	**n/a**
X direction	**69.8**	**49.7**	**5.0**	**6.9**	11.35-11.43
Z direction	**67.9**	**49.3**	**5.1**	**5.6**	**11.37-11.40**

Table 2. Material properties measured for the three I-70-H (special) ITTT billets compared to the Brush Wellman specification for standard I-70-H Bc.

Grinding and polishing took place at HDOS wherein the initial grinding stages the surface contour of the primary mirror was measured using a WEGU coordinate measuring machine. Once the surface figure and finish were sufficiently reduced, interferometric testing was utilized with a null lens in a center of curvature test. The hyperbolic figure of the primary mirror was obtained with a combination of large tools in a plunge configuration, as shown in figure **4, and** with computer cent rolled small tools, as shown in figure **5.** The center of curvature metrology test tower is shown with the primary mirror in **figure 6.** Figure 7 illustrates the configuration for measuring the surface roughness using a WYCKO Topo 2D.

The mirror was thermally cycled between 77 K and 473 K for more than twelve cycles during grinding and polishing. Polishing of the bare Be surface was interspersed with frequent thermal cycling for stress relief. After completion of the initial polishing phase, the mirror had a surface figure at room temperature of **0.2** λ rms at λ = **0.63** μm. The mirror was tested in this condition at JPL and returned to HDOS. After further polishing the figure was reduced to 0.101 **rms as shown in figure 8.**

The mirror is physically 88.5 cm OD, 29 cm ID, 4 cm thick at the center with a vertex radius of approximately 2 m and weighs 14 kg. The outer edge thickness is only 6 mm. The mirror assembly is shown in figure 9. It was shipped in this configuaration to JPL for cryogenic testing.

4. CRYO-TESTING

The ITTT primary mirror assembly (PMA) was tested in the SIRTF Telescope Test Facility (STTF) at JPL. The details of the design and construction of the STTF have been described previously.1 [1,12] Briefly, the facility consists of three concentric shells as shown in figure 10. The outer shell maintains vacuum, the intermediate shell is cooled to 77 K by a single liquid nitrogen tank at the base, and the inner shell is cooled to 4 K by dual liquid helium tanks at the top and bottom. The upper tank also supplies cryogen for cooling a vibration isolated precision gimbal mount and the experimental hardware. Each of the tanks has a cylindrical hole through its center to allow light to pass. Near the base, arc two shutters, an inner one at helium temperature and outer one at nitrogen temperature. These are normally closed and can be easily and quickly

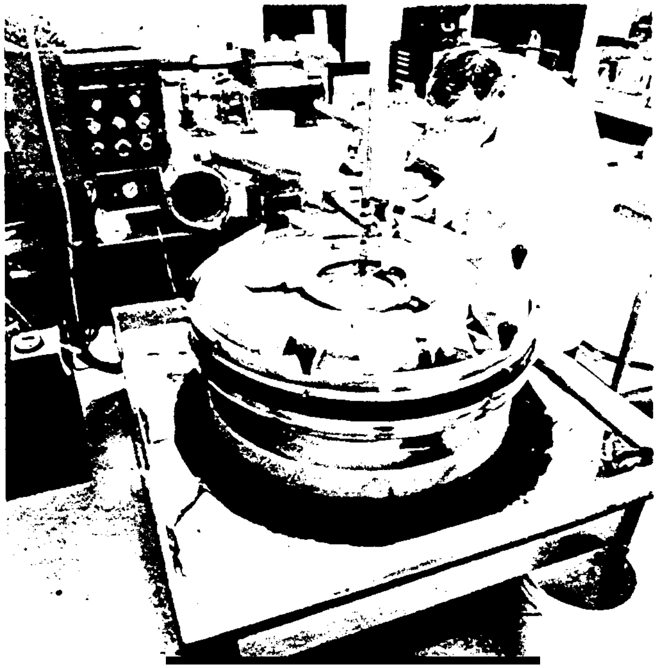

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Figure 4. Photograph of full aperture polishing of the primary mirror.

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Figure 5. Photograph of computer assisted figuring of the primary mirror with a small polishing tool.

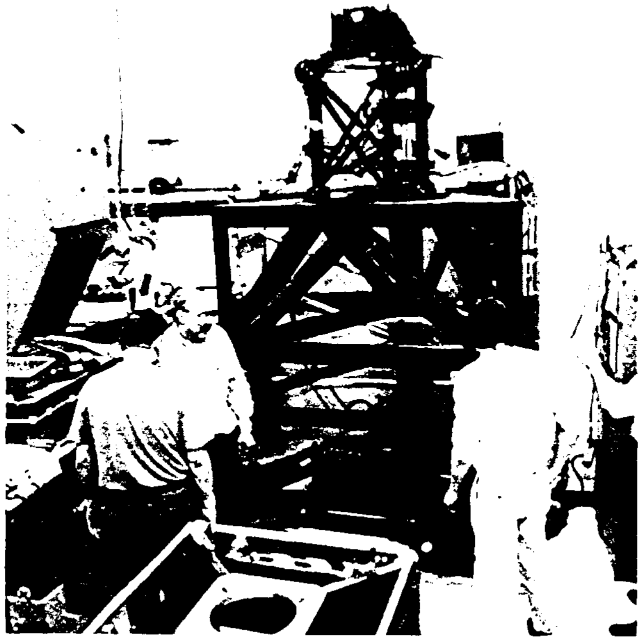
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Figure 6. Photograph of primary mirror in the interferometric test station for in-process full aperture figure testing.

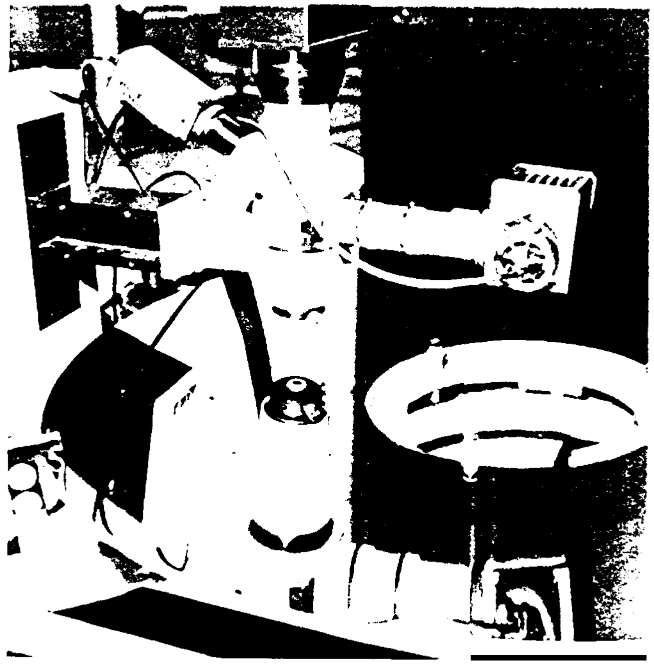
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Figure 7. Photograph of primary mirror in WYCKO TOPO 2D for surface roughness measurement.

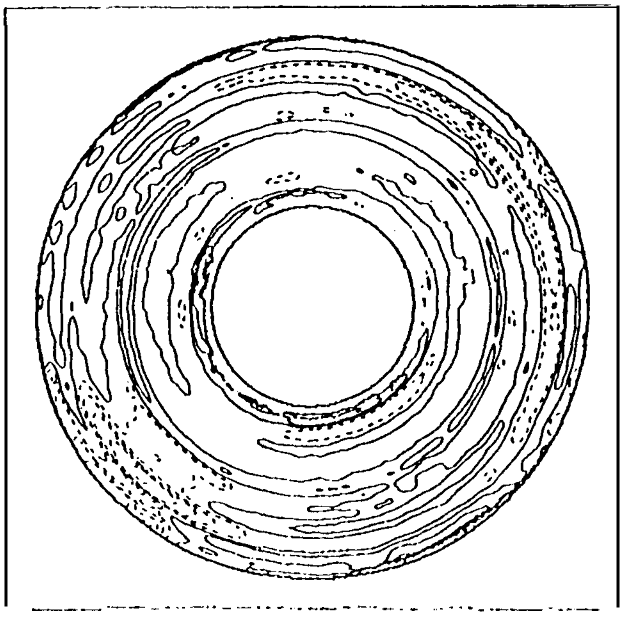
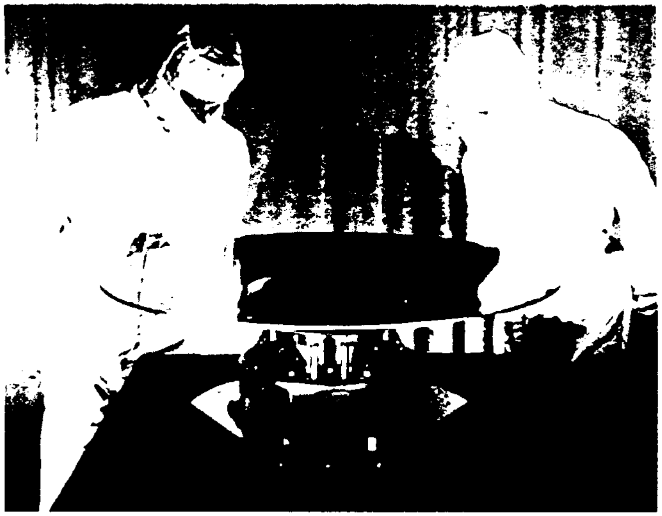


Figure 8. Contour map of the room temperature primary mirror surface figure over an aperture of 80 cm after zonal correction polishing (contour interval = 0.10 λ). Piston, tilt, focus and coma have been removed from the data. Surface figure = 0.10 λ rms, 1.1 λ peak-to-valley.

opened prior to measurement. The base of the vacuum shell has an optical window, below which is an instrument rack supporting a turning mirror, a null lens and the Zygo GPI phase shifting visible (0.633 μm) interferometer. The entire assembly, tank and instrument rack is mounted on a large aluminum triangular frame which rests on three Newport pneumatic vibration isolation legs.

For testing, the PMA was mounted on an aluminum adapter plate with three aluminum biped flexures. The adapter plate was attached to the STTF gimbal via three titanium flexures and the gimbal/PMA assembly was attached to the baseplate of the upper helium tank with the mirror facing down. Copper straps from the aluminum adapter plate to the tank baseplate provided cooling and platinum resistance thermometers bonded with silicone adhesive to the PMA at various points provided a means to monitor temperature.

After loading the PMA the tank was evacuated, normally overnight, baseline room temperature interferograms were recorded, and cooling was commenced. The time required to cool the PMA to 77 K from room temperature was approximately 80 hours. During cooldown, gradients across the PMA were limited to <10 K. Once the PMA equilibrated at 77 K, more interferograms were typically recorded. Cooling to liquid helium temperature and equilibration required approximately another 12 hours.



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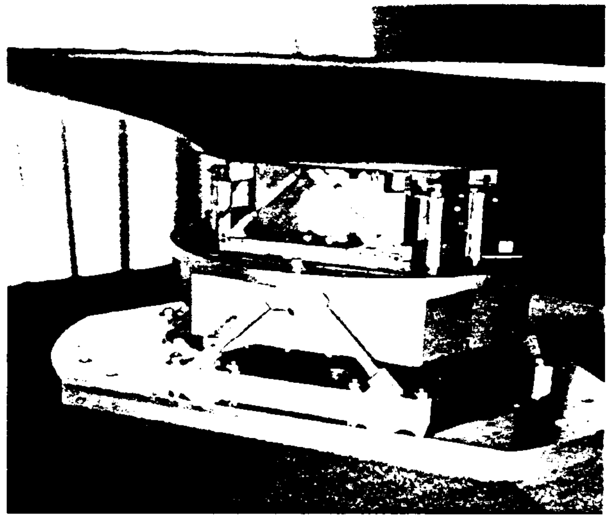

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Figure 9. Photographs of primary mirror assembly attached to adapter plate: left) overall view of finished assembly showing polished mirror and ID aperture stop; right) close-up showing bipod flexure attachments between mirror and bulkhead, and between bulkhead and adapter plate.

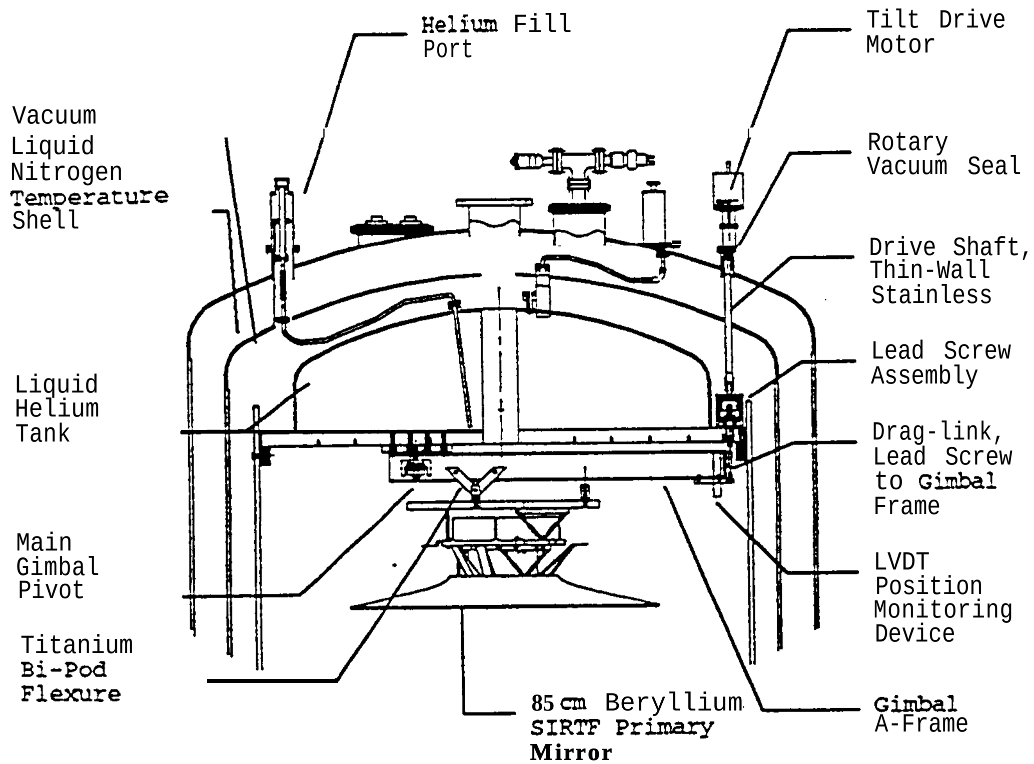

Figure IO. Schematic of SIRTF Telescope Test Facility upper tank assembly with gimbal and ITTT primary mirror assembly installed.

Following equilibration at 4.8 K, measured gradients across the PMA were <0.5 K. Interferograms were once again recorded and the facility was allowed to warm up. The warm up and equilibration time to room temperature was approximately 90 hours at which point final interferometric data were recorded.

The initial measurements on the PMA at room temperature showed an rms surface error of 0.19 λ (λ = 633 nm) with a peak-to-valley error of 1.56 λ over the 85 cm aperture. The dominant error feature was a series of concentric zones ≈1-2 waves in height. Over a period of several months, the PMA was cycled five times to 77 K and three times to 5 K and showed no evidence of hysteresis. Room temperature data recorded following these multiple cycles showed an rms surface error was **0.19** λ and the peak-to-valley error was 1.35 λ. The uncertainty in the rms surface error measurements recorded at JPL arc estimated to bc ≤ ±0.02 λ.

Measurements on the PMA at low temperature did reveal, as anticipated, a moderate cryogenic distortion, including the appearance of a "high edge" around the OD of the mirror making it impossible to record reliable interferometric data in an annulus 1-2 cm wide. The cryogenic data are thus reported over an aperture of only ≈ 81 cm. Therms surface error recorded at 77 K was found to be 0.58 λ and the peak-to-valley error was 4.421. The results at 5K were essentially identical to those at 77 K, showing an rms surface error of 0.59 λ and a peak-to-valley error was 4.30 λ. Over multiple cycles, the data were highly reproducible. A contour map of the difference in surface figure between cry and ambient is shown in figure 11. It shows the difference, or the thermal distortion in the mirror, to bc 0.71 λ.rms.

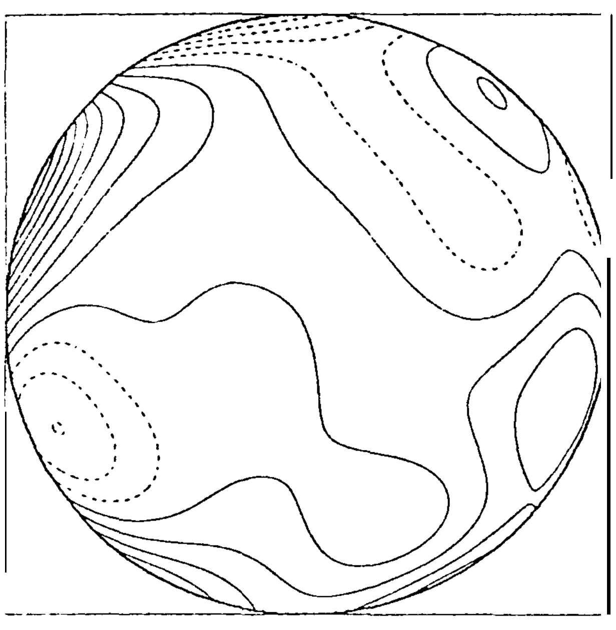

Figure 11. Contour map generated from a 37 term Zcrnikc fit of the figure difference bctwccn 77 K **and room temperature for the** ITTT primary mirror. **The** difference is 0.72Zrms,7.01 **peak-to-valley. (Contour interval = 0.50 λ)**

With the observation of the cryogenic distortion in the PMA, an investigation ensued to determine its source. The possibility of systematic errors in the test set-up was investigated by rotating the test hardware 120° and subsequently rotating the null lens 180°. [n each case, the cryo-distortion rotated with the hardware. The PMA was then decoupled from the aluminum adapter plate and biped flexures and suspended from a simple three point kinematic mount. No change in the cryo-test data was observed, Following that, the primary mirror was removed from the PMA and itself cryo-tested using the same three point mounting scheme. The observed error in the primary mirror matched the error measured in the PMA thus indicating that the source of the cryo-distortion was in the mirror itself and not in the mounting hardware. Finally, the entire PMA was reassembled and measured once again at 5 K essentially identical results as those measured earlier.

5. CRYO-NULL FIGURING

The proposed solution to the cryogenic distortion problem was to "null-figure" the mirror. Detailed interferometric data were recorded on the PMA at room temperature and at 5K prior to shipping the hardware back to HDOS. The plan was to attempt to remove the concentric zones and null figure the mirror over an ≈80 cm aperture in such a manner so as to achieve the correct shape at 5 K. This process was accomplished with computer controlled polishing using small tools. No attempt was made to eliminate the high edge since it would have required many hours of computer controlled polishing with a very small tool. It was felt that this process could be attempted in a subsequent refiguring cycle if the initial efforts proved successful.

Following the refiguring, the PMA was returned to JPL. Initial room temperature measurements showed that the concentric zones had been substantially reduced in depth to 0.5 λ or less. The rms surface error was measured to be 0.44 λ and the peak -lo-valley error was 3.45 λ as shown in figure 12. The significant degradation of the surface figure quality at room temperature was, of course, to be expected due to the nature of the null-figuring process. Notice in the figure that the highs of figure 11 have become lows in figure 12, and vice-versa

Cooling the PMA to 77 K revealed an rms surface error of 0.151 and the peak -to-valley error was 1.38 λ over an ≈80 cm aperture. The hardware was cycled three times between room temperature and 77 K. Both the room temperature data sets and the 77 K data sets were consistent over these cycles. A subsequent attempt was made to cool the hardware to 5 K, however, due to a problem with the test facility, the PMA only reached a temperature of ≈20 K. The surface figure recorded at 20 K was essentially the same as that recorded at 77 K. These results represent a factor of approximately 4 improvement in surface figure of the PMA at cryogenic temperature over the pre null-figuring data and are consistent with the SIRTF requirements. They indicate that the refiguring process has been very successful and that null figuring has been demonstrated on a Be mirror to a level never before achieved. Further tests at 5 K are planned, but no significant changes are anticipated. A decision on whether to attempt a further refiguring cycle to attack the high edge will be forthcoming. In the interim, the other telescope components have been completed as shown in figure 14 and await assembly.

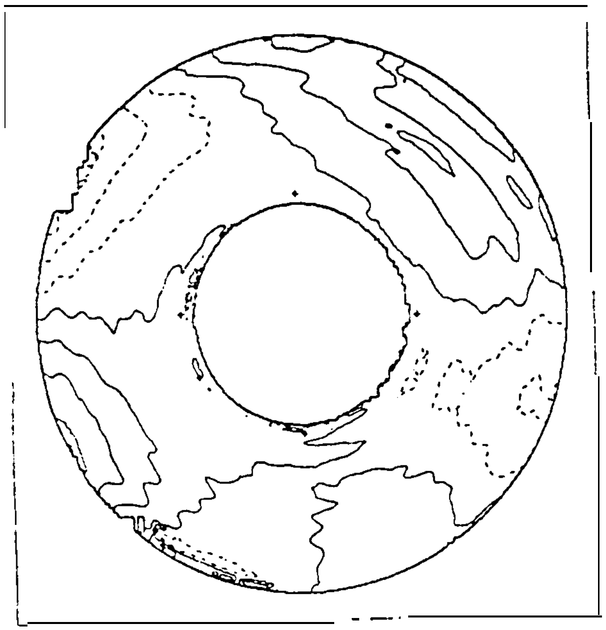

Figure 12. Contour map of ITTT primary mirror at room temperature after null figuring (contour interval = 0.50 λ) Figure = 0.49 λ rms, 4.14 λ p-t-v

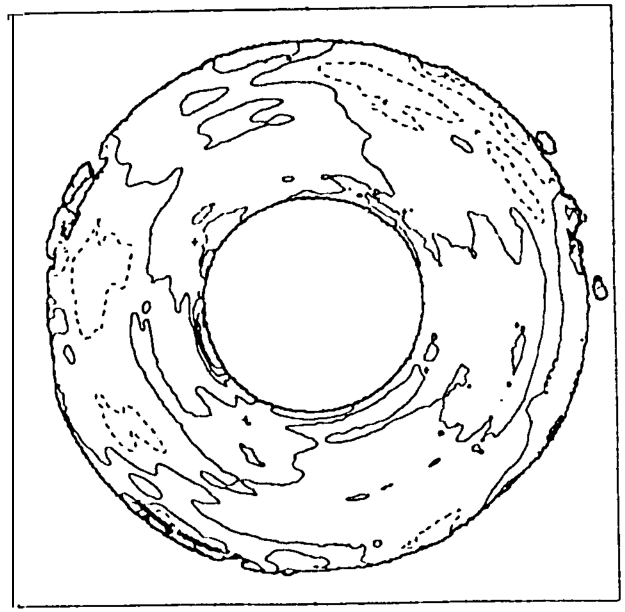

Figure 13. Contour map of ITTT primary mirror at 77 K after null figuring (contour interval = 0.25 λ) Figure = 0.16 λ rms, 4.85 λ peak-to-valley.

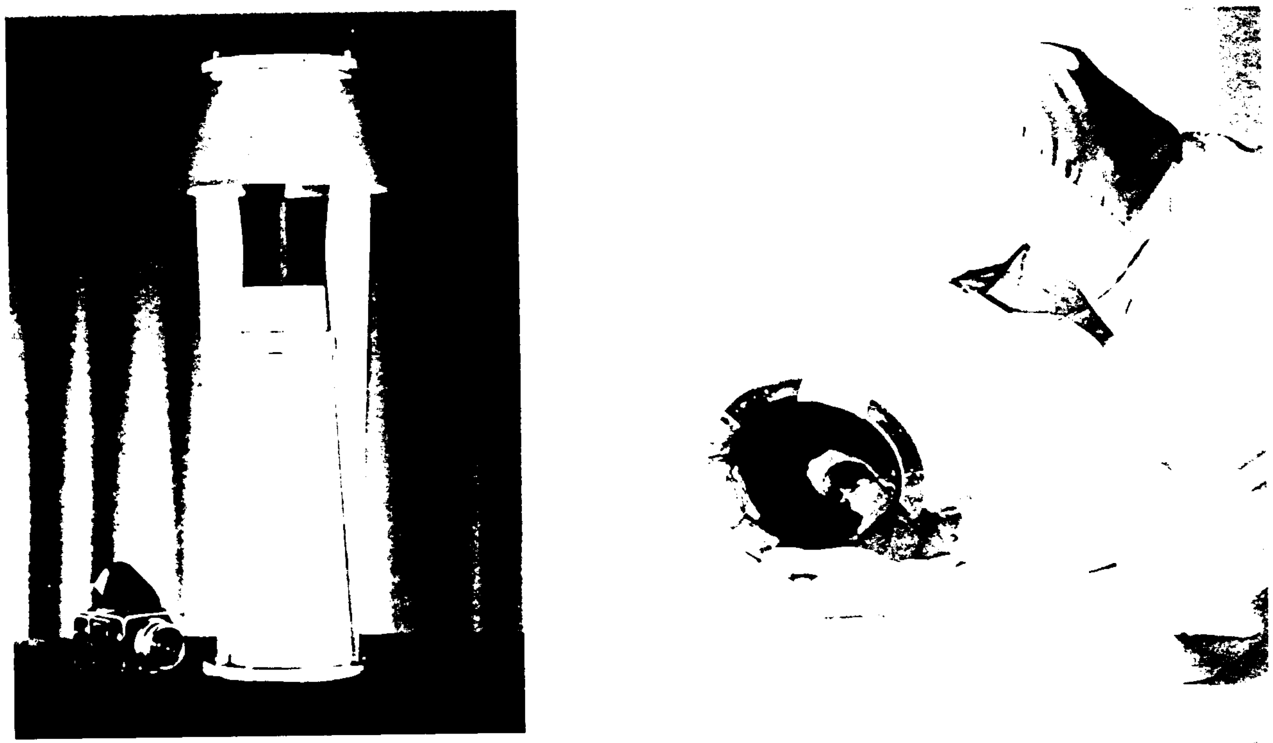

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Figure 4. ITTT components: left) central metering tower showing primary and secondary cone baffles and support ribs; right) finished secondary mirror assembly.

6. CONCLUSIONS

The results of this program confirm the validity of the choice of Be in a central metering tower ultra-lightweight configuration to meet SIRTF program requirements. While the ITTT has not yet been cryogenically tested as an optical telescope assembly, the successful cryo-null figuring and resulting cryogenic performance of the primary mirror assembly with no thermal cycling hysteresis demonstrate that this ultra-lightweight design can meet all performance targets for SIRTF and the manufacturing processes provide maximum stability..

The telescope design is extraordinarily efficient and provides an 85 cm aperture telescope that has a mass of less than 30 kg and is still rigid enough to meet SIRTF requirements. The central metering tower and small diameter bulkhead are the key elements in the design along with the very thin single arch primary mirror.

The manufacturing methods used to fabricate the ITTT demonstrate that for ultra-stable Be mirrors the following methodology works:

- Start with clean, fine grained, moderate to low oxide, impact ground Be powder,
- Consolidate by HIP
- Use progressive machining for all steps,
- Acid etch after every machining and every rough grinding step,
- Anneal at 785°C after HIP and every rough machining step and
- Thermal cycle after the last machining step and after every grind and polish step..

The specified processes yield high quality homogeneous and isotropic Be with properties that consistently exceed the manufacturer's specifications. Utilizing this technology, ultra-lightweight, ultra-stable Be mirrors and systems can be specified with confidence

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