SIRTF telescope optical engineering

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ABSTRACT

The Space Infrared Telescope Facility (SIRTF), a cryogenic infrared observatory planned for launch around the turn of the century, will span the 3 - 180 µm spectral waveband during its operation in an earth-trailing heliocentric orbit, SIRTF's environmental conditions and mass constraints present challenging requirements to the optical engineer. The SIRTF telescope will operate at near liquid helium temperatures after encountering a launch environment. The Optical Telescope Assembly (OTA), which incorporates the primary and secondary mirrors, baffles and support structure, must retain alignment after launch vibration, gravity release and cooldown. Additionally, telescope mass requirements indicate the use of lightweight primary mirror technologies for SIRTF. Candidate primary mirror substrates include fused silica, beryllium, and silicon carbide. Each material has its set of trade-offs. This paper presents these telescope engineering issues and how the SIRTF telescope technology plan addresses them in order to facilitate the final design.

1. INTRODUCTION

SIRTF has undergone recent replanning to address new cost constraints while defining a scientifically compelling mission faithful to the Bahcall report priorities and responsive to recent scientific developments.[1] A warm launch / cold operation telescope concept has been introduced, where the dewar encloses the instruments but not the telescope. In this concept, the telescope is launched at 300 K. After passive radiative cooling, followed by helium vapor cooling, the telescope will operate at around 5.5 K in space. In the cold launch concept the telescope is in the dewar and launched at operating temperature (< 4 K). In either concept, the instruments stay at ~1.5 K from launch to orbit. Figures 1 and 2 depict the SIRTF warm and cold launch concepts, respectively. This paper presents an OTA point design generated for preliminary warm launch study, concentrating on optical components.

2. OTA REQUIREMENTS

The OTA is the integrated assembly of the following components:

- Primary mirror
- Secondary mirror
- Primary mirror mount
- Secondary mirror mount and focus mechanism
- Support structure
- Stray light baffles
- Black coating

Three (3) major requirement levels[2] drive the OTA design. All requirements are specified by levels to identify the requirement flow and scope as described in the following table.

Table 1 - Requirement levels

Level 1 requirements	- flow from NASA Headquarters to the project represents the minimum set necessary to achieve the scientific objectives of SIRTF, as agreed upon by NASA and the SIRTF scientific community
Level 2 requirements	- developed by the project - levied onto each project segment (the observatory, science mission and operations, and launch vehicle)
Level 3 requirements	- flow from the project segment - scope within a system

Table 2 presents requirements placed on the OTA at levels 1, 2, and 3. Obviously, additional requirements (primarily at lower levels) will be specified as the SIRTF design progresses.

Table 2 - OTA driving requirements

Level 1	
• Aperture diameter:	85 cm
• Image quality:	≤ 2.0 arc seconds@ $\lambda = 3.5\ \mu m$ (50% encircled energy diameter)
. Stray light:	Statistically insignificant compared 10 background
. Spectral range:	3 - 180pm (spectral throughput: TBD)
Level 2	
• System f/#:	12
• Maximum central obscuration:	14 % (area)
• Back focal distance:	100 cm
• Temperat urc:	5.5 K
• Telescope degree of polarization:	≤ 5% for $\lambda = 3 - 5\ \mu m$ ≤ 1 % for $\lambda = 5 - 180\ \mu m$
Level 3	
• OTA performs in O G, is testable in 1 G.	
. Wavefront error power spectrum:	TBD
• Mirror substrate surface roughness:	TBD

3. MATERIALS

The OTA design depends strongly on the primary mirror material selected. Three (3) candidate primary mirror substrates arc beryllium, silicon carbide and fused silica. These materials allow two (2) basic OTA design classes:

- Monometallic OTA - for beryllium and silicon carbide minors
- Polymaterial OTA - for a fused silica mirrors

The following three (3) subsections address these design approaches and material selection issues.

3.1 Monometallic OTA

Beryllium and silicon carbide allow a monometallic OTA design (except for inserts and other relatively small items) sinew they can form practical structural components. in this case mechanical stresses duc to differential thermal expansion arc significantly reduced (eliminated for homogeneous, isotropic materials). The OTA scales over temperature and theoretically, a system in focus at room temperature (and mechanically fixed at the focal plane) remains in focus al all temperatures. However, these inhomogeneous metals exhibit thermal hysteresis (dimensional change upon temperature cycling and return to reference temperature) and temporal hysteresis (dimensional change over time) which can adversely affect mirror performance and impede cryofiguring (discussed later).

3.2 Polymaterial OTA

A fused silica mirror' requires a careful mirror/mount design. Fused silica dots not make practical structural components so the OTA design will involve at least two (2) materials. As a result, differential thermal expansion may induce stresses that deform or break the mirror. The design must also withstand temperature cycling anti launch vibration. On the positive side, fused silica has preferred optical characteristics. Fused silica optical fabrication methodologies arc standard. It is also a homogeneous material, and dots not exhibit temporal and thermal hysteresis.

3.3 Material selection issues

'1'able 3 summarizes key OTA material selection issues. The discussion following the table details selected material attributes.

~'able 3 - OTA material selection issues
(for cryogenic, lightweighted, 1 meter class mirrors)

Attributes	Open back beryllium	React ion bonded silicon carbide	Conservative fused silica	Ultra light fused silica
Ease of mirror mounting	demonstrated on IRAS	not yet demonstrated	developed under 1s0	1101 yet demonstrated
Cryo-fract urc mechanics	not applicable	maybe n/a	Unknown	unknown
Gravity distortion	small	small	bad	unknown/bad
Mirror quality test temperature	< 60 K	< 6 0 " K	< 10K	<1OK
Hysteresis to 4K	OK for IRAS	unk I1OR'I)	good	unknown
CTE uniformity	adequate	unknown	good	unknown
OTA mass	low	low	high	unknown due to mount
Mirror thickness	thin	thin	acceptable	unknown/thin
Response 1 0 launch environment	OK for IRAS	unknown	OK for 1S0	unknown
Manufacturing database	incomplete	conceptual	no mounts	no mounts
Potential OTA stability	< 10 µm	< 10 µm	~ 25 µm	-25 µm
Likelihood of quilting	unlikely	unlikely	possible	possible
Cryofigurability	OK for IRAS	unknown	good	unknown
Cryo mirror database	IRAS	none	ISO	none

Ease of mirror mounting:

- Beryllium: Be is a structural metal with conventional machining practices (except that Be dust must be controlled). Additionally, Be is unique with regard to its low Poisson's ratio.[3] IRAS demonstrated a mirror mounting methodology for beryllium.

- Fused silica: The material brittleness, fracture toughness and Poisson's ratio (().17) of glass complicates its mounting.[3] The only flight-mounted fused silica mirror cooled to liquid helium temperatures that wc know of is the Infrared Space Observatory (1S0) primary mirror.

- Ultralight fused silica: Mirror mounting technology appears to be developmental. To the best of our knowledge, no ultralight glass mirror has been mounted and cryogenically tested. Although ultralight mirrors retain strength 10 weight characteristics of lightweight mirrors, their absolute stiffness is reduced in proportion 10 their mass. Thus, external forces will generally affect the figure of ultralight mirrors nmrc than lightweight mirrors.

- Reaction bonded silicon carbide: Mounting techniques arc closer to those used for metal mirrors than glass mirrors. The ceramic nature of SiC structures provides some flexibility beyond both metals and glasses in structuring mirror components, although simple machining such as drilling and tapping arc not possible because of SiC hardness,

Cryo-fracture mechanics: At the present time, we have no open literature citations for cryogenic fracture mechanics data on these mirrors or their base materials. It is our intent to include a cryogenic fracture mechanics test activity in the technology program to obtain engineering design data on this parameter.

Mirror' quality test temperature: Be and SiC mirrors do not change their shape as much as glass mirrors below liquid nitrogen temperatures. (Bc and SiC has a very low integrated CTE in this temperature regime.) This allows running some in-process tests, such as mirror blank quality tests, at liquid nitrogen rather than liquid helium temperatures. This shortens test cycles. Liquid helium tests arc still required for the completed mirror and OTA tests.

CTE uniformity: Glass is available with excellent CTE performance, although wc have no data on ultralight mirrors where several pieces of glass with very high surface to volume ratios arc frit bonded with a CTE "matched" material (surface to volume ratio is important because very thin glass parts arc sensitive to surface stresses).

OTA mass: Current mass allocations arc based on a beryllium OTA. Glass mirrors generally require a higher mount mass than beryllium to provide an acceptable interface between the different mirror and mount materials. This mass can be allocated to Bc or SiC primaries for stiffer mirror designs to improve wavefront quality and reduce gravity distortion.

Response to launch environment: To the best of our knowledge, the only large, liquid helium cooled mirror to be launched is the beryllium IRAS mirror, which performed within specification after launch. 1S0 will be the first glass mirror (not yet launched). It hrrs apparently survived simulated launch exposure. There arc no known data on onc-meter class, liquid helium cooled, ultralight glass or silicon carbide mirrors (even with a simulated launch environment).

Manufacturing database: Glass mirror manufacturing is the most advanced of any material, based on centuries of practical experience and with numerous recently developed tools for cutting thin sections and low pressure ion milling techniques. Silicon carbide represents the other extreme. Large SiC mirrors have not yet been made and the base material is very hard. SiC manufacturing methods are under development and rapidly evolving but not well established. Large Be mirrors have been manufactured, but except for IRAS, all the mirrors larger than 0.5 meters have been manufacturing experiments. The S1 RTF telescope technology plan builds on these experiments.

Potential OTA stability: The SIRTF telescope optical design has a secondary mirror longitudinal magnification ratio of 100. Therefore, primary-to- secondary mirror spacing errors/cimngcs cause image plane defocus, magnified by that amount. Be and SiC structures promise better spacing control (not demonstrated) than shown possible by experience with metered glass assemblies. At this time wc plan to incorporate a secondary mirror focus mechanism in the OTA to correct despace and mirror radius of curvature deviations.

Likelihood of quilting (print-through of a cored mirror structure): This **is not a problem for lightweighted glass** (based on ISO and NASA Ames data). Wc selected an open back mirror structure to avoid it on beryllium. Any statement on ultralight glass or SiC would be speculation.

Cryofigurablity: Cryofiguring (discussed in section 4) improves mirror cryogenic wavefront quality. The IRAS beryllium primary mirror was successfully cryofigured.[4] NASA Ames demonstrated this technology on fused silica[5] (a high quality fused silica mirror may not even require cryofiguring). It is not known if ultralight glass or SiC mirrors would require cryofiguring, or if it could be done (ultralight glass may have high spatial frequency errors which arc difficult 10 remove).

Surface scatter (not in table 2): Beryllium has anomalous surface scatter associated with grain boundaries in the polished surface. A beryllium or aluminum coating can correct this effect. Both glass and SiC may be polished for low scatter.

4. PRIMARY MIRROR

Based on the measured performance of large cryogenic mirrors, the primary mirror will be a principal contributor to the telescope wavefront error. Table 4 summarizes the SIRTF telescope primary mirror specifications. Current requirements indicate a primary mirror rms wavefront error requirement in the 0.3 λ (@ 0.6328 μm) range. Mirror performance in earlier, unclassified, cryogenic IR satellites (50 cm or greater aperture diameter) do not meet this requirement. IRAS and 1S0 primary mirrors have wavefront errors of 0.68 and 0.59 rms waves @ 0.6328 μm, respectively.[6] To meet the SIRTF requirement, wc need improved materials technology and/or cryofiguring.

Cryofiguring uses mirror phase maps taken at cryogenic temperatures to refigure the mirror (at ambient temperature) for improved cryogenic performance. This technology was demonstrated on beryllium for IRAS and on fused silica at NASA Ames Research Center. Continual improvements in phase shifted interferometry (increased spatial resolution, improved software) and numerical controlled polishing techniques should yield improved results. Research in this area is active. An Ames Research Center team currently performs cryogenic mirror wavefront quality tests for SIRTF at their cryogenic optical test facility (COTF).[7,8] Tests have been ongoing at COTF since the early 1980's. The Ames-COTF team has:

'1'able 4- Primary mirror specifications

Clear aperture diameter	85 cm
Primary mirror f/H	1.2
Vertex radius of curvature	204 cm
Shape	Hyperbolic
Mass	18 kg (baseline)
Operating temperature	S. S_K
Wavefront quality	0.3 λ TON{@ 0.6328 μm)
Wavefront error power spectrum	TBD
Candidate materials	beryllium, silicon carbide, fused silica
Coating	TBD

- generated mirror phase maps at room, LN_2 and LHe temperatures to measure absolute and differential figure errors in various beryllium and fused silica mirrors
- developed thermal strap methodologies to effectively link test mirrors to the COTF cold plate without mirror distortion
- demonstrated cryofiguring
- evaluated mirror cooldown rates and thermal gradients

5. TECHNOLOGY DEVELOPMENT

The SIRTF telescope technology plan addresses OTA critical issues to mitigate cost, schedule and performance risk. This is important since SIRTF telescope requirements exceed the performance demonstrated in the available database for cryogenic, turlf-meter 10 one-meter class IR satellites. The telescope technology plan objectives are to:

- fill gaps in the material properties database
- mitigate cost and schedule risk by establishing design, fabrication, integration and test methodologies in required areas
- establish the feasibility of meeting performance requirements within OTA mass allocations
- qualify a flight configured OTA, including stray light performance

To expand the database, we will perform cryogenic optical tests of candidate mirror materials with various lightweighting methodologies. Different materials uniquely affect the OTA design trade space. A beryllium primary mirror allows the benefits of a single-matcl-ial OTA, and low mass, but tests demonstrated less than desirable figure quality.[9] Unmounted fused silica mirrors demonstrate better cryogenic wavefront quality[5] than beryllium, but mirror mounting and mass become critical issues, We have no cryogenic test data on mounted ultralight fused silica and silicon carbide mirrors. An ongoing 50 cm mirror testing program addresses OTA technology issues within current cost and facility constraints. This spring, we expect delivery of two (2) new sO cm spherical mirrors, one (1) each beryllium and silicon carbide, for evaluation at COTF as part of tile SIRTF telescope technology program. In addition to using phase-shifted interferometry to general c mirror phase maps, we will implement a cryogenic point spread function lest (also called a star test[10]) at COTF to examine the mirror wavefront qualitatively. Results from these tests will provide data for the 85 cm SIRTF primary mirror design. Mirror and materials issues we want to resolve include: cryofiguring, cryogenic optical test methodology, edge effects on mirror figure, mirror manufacturing process specifications, surface quilting (print-through), gravity effects, mirror mount effects, schedule and cost, thermal properties, blank anisotropy, and material hysteresis.

Wc can also improve the mirror manufacturing approach. Ncw optical test and mirror figuring equipment (as described in section 4) or multiple iterations (the IRAS beryllium primary minor was only cryofigured once) should improve mirror wavefront quality through cryofiguring. Ncw mirror fabrication methodologies demonstrated by industry also imply better mirror performance. This area includes improvements in: raw materials (spherical beryllium powder to increase material packing density for hot isostatic pressing over standard Be powders), materials processing, lightweighting (water jet milling to generate lightweight glass structures), and figuring (numerically controlled ion beam techniques).

6. CONCLUSION

The SIRTF telescope requires some performance improvement over known satellite observatories in the same class. The ongoing telescope technology program addresses this issue on multiple fronts, including optical tests of various mirror substrate materials and ncw fabrication methodologies. Enabling technologies include recent developments in cryofiguring and lightweighted mirror manufacturing techniques. This will facilitate primary mirror material selection and convergence toward the final design,

7. ACKNOWLEDGMENTS

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8. REFERENCES

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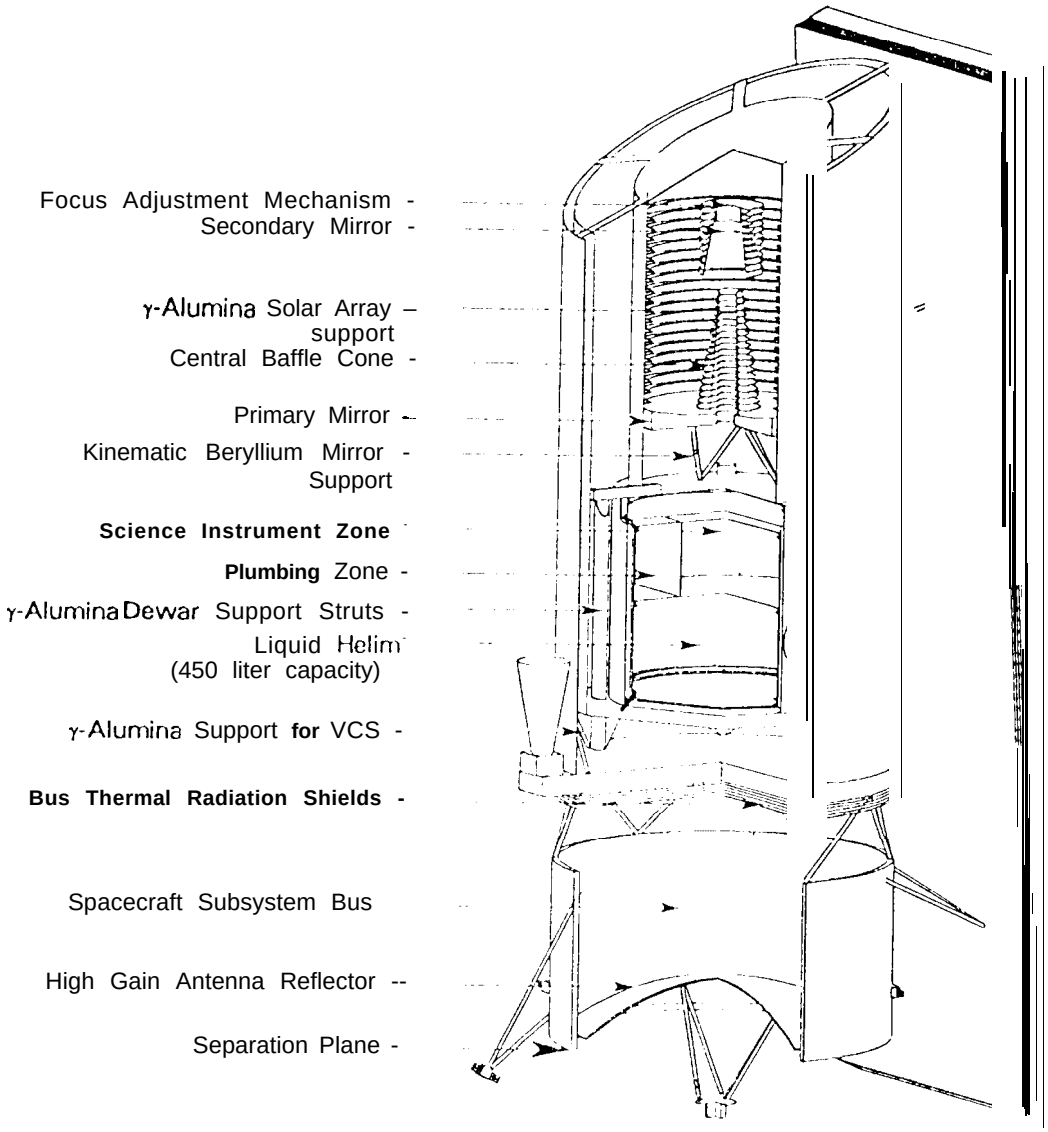

Figure 1 - SIRTF Warm Launch Concept

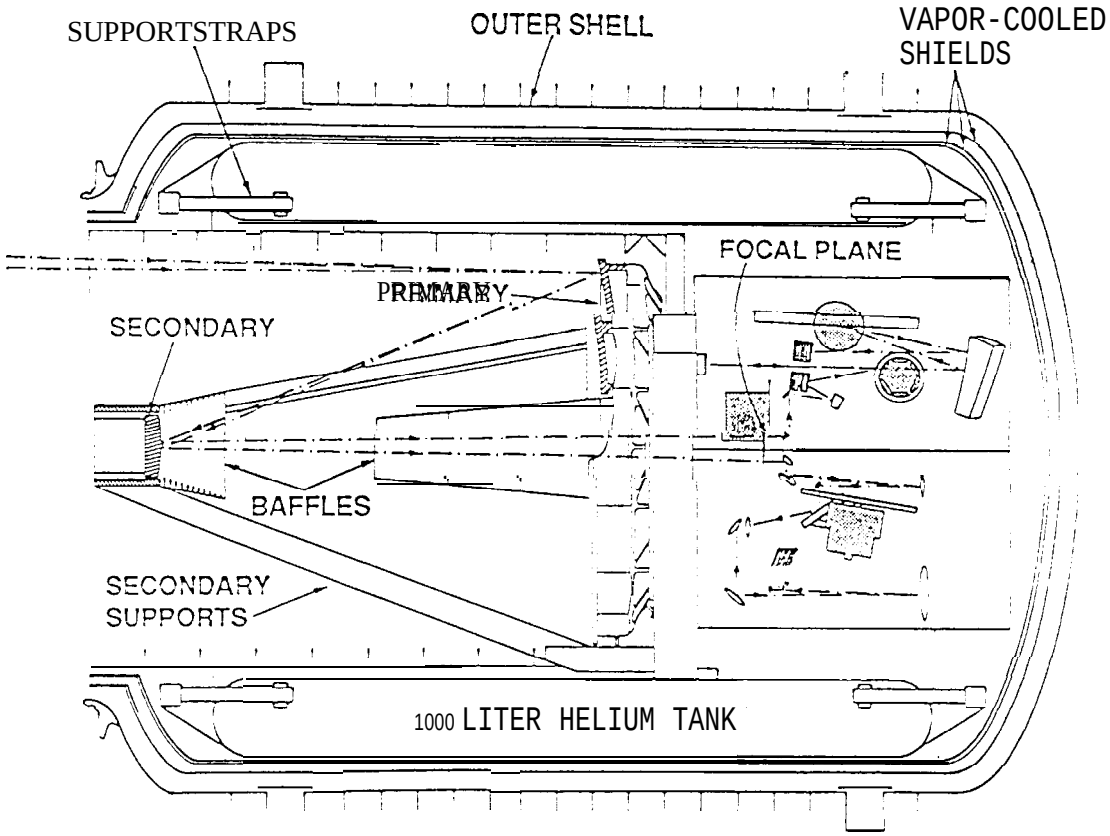

Figure 2 - SIRTF Cold Launch Concept