# Architecture of the FIRST Telescope

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## ABSTRACT

The Far Infrared and Submillimeter Telescope (FIRST), is an ESA cornerstone mission, that will be used for photometry, imaging and spectroscopy in the 80 to 670 μm range. NASA, through the Jet Propulsion Laboratory (JPL), will be contributing the telescope and its design to ESA. This paper will discuss the work being done by JPL and Composite Optics, Incorporated (COI), the developer of the primary mirror technology.

Optical and mechanical constraints for the telescope have been defined by ESA and evolved from their trade studies. Design drivers are wave front error (10 μm rms. with a goal of 6 μm rms.), mass (260 kg), primary mirror diameter (3.5 m) and f number (f/0.5), and the operational temperature (less than 90 K). In response to these requirements a low mass, low coefficient of thermal expansion (CTE) telescope has been designed using carbon fiber reinforced polymer (CFRP).

This paper will first present background on the JPL/COI CFRP mirror development efforts. After selection of the material, the next two steps, that are being done in parallel, are to demonstrate that a large CFRP mirror could meet the requirements and to detail the optical, thermal and mechanical design of the telescope.

**Keywords**: FIRST, telescope, far-infrared, CFRP, composite, mirror, CTE, CME, thermal gradients, stray light

## 1. INTRODUCTION

The FIRST mission will be the first far-infrared submillimeter observatory in space to cover the 80 to 670 μm range. This range of wavelengths cannot be observed from the ground due to atmospheric absorption. Some coverage of this band was obtained by the Infrared Astronomical Satellite (IRAS), an all-sky survey mission, that covered 4 bandwidths the longest being 100 μm. ISO recently covered the 3 to 200 μm range with a 0.6 m diameter, liquid helium cooled aperture. Balloon-borne telescopes can achieve reasonably good viewing in this wavelength range for short periods of time. The largest is PRONAOS with a 2 m aperture that observes from 180 to 1,200 μm. The Kuiper airborne observatory was able to cover this range with a 0.9 m aperture telescope and is being replaced by SOFIA with a 2.5 m aperture telescope.

FIRST will have a 3.5 m aperture and will be passively cooled to between 70 and 90 K in an orbit about L2, 1.2 to 1.8 x $10^6$ km from the Earth (see figure 1). At this orbit there will be almost continuous viewing. A sunshade protects the telescope from the sun at all times and is configured to allow the telescope boresight to tilt 30° towards the sun. Sky coverage at any time is $2\pi$ steradians by allowing the boresight to rotate $2\pi$ about the sun vector and tilt towards and away from the sun vector by a maximum of 30°. Figure 2 shows the telescope and sunshade.

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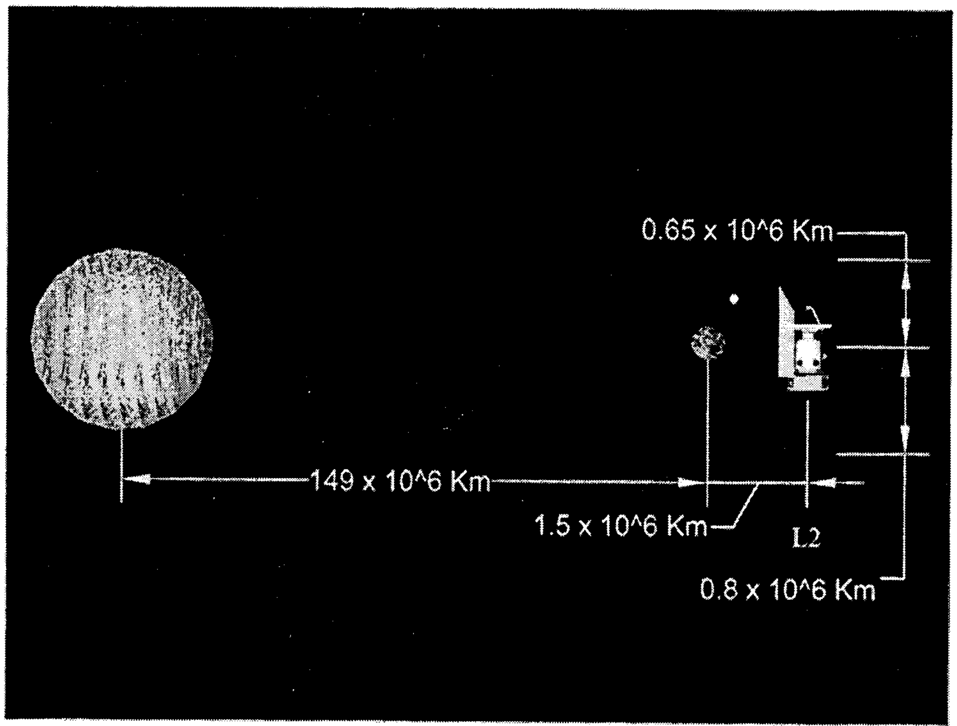


Figure 1. Position of Spacecraft, Earth and Sun with Respect to L2. L2 is $1.5 \times 10^6$ km from Earth. The orbit of FIRST takes it $0.65 \times 10^6$ km above and $0.8 \times 10^6$ km below L2.

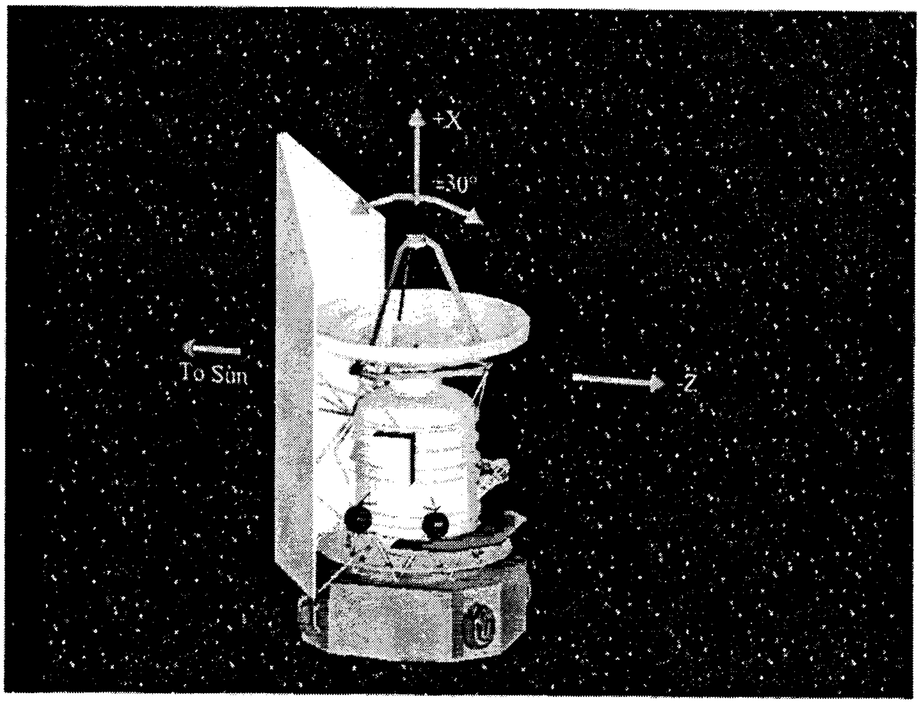


Figure 2. FIRST Spacecraft Showing Coordinate System, Sun Direction and Tilt Angle

Three focal plane instruments are fed by the telescope with an f/8.68 beam. All instruments are cryogenically cooled and share the focal plane. The heterodyne instrument for FIRST (HIFI)[1] is strictly a spectrometer while the photoconductor array camera and spectrometer (PACS)[2] and the spectral and photometric imaging receiver (SPIRE)[3] are both spectrometers and imaging photometers. The optical design of the telescope is given in reference 4 and the primary mirror design is discussed in references 5 and 6.

## 2. HISTORICAL BACKGROUND

Both ESA and NASA have studied various versions of this observatory for the past 20 years. A 20 m aperture Large Deployable Reflector (LDR) concept came about in the US in 1979 and in roughly 1981 ESA began to study an 8 m diameter aperture version of FIRST. Beginning in 1986 NASA decided that a smaller precursor mission was needed and studied first a 4 m and then a 2.5 m Submillimeter Explorer Mission. In 1986 NASA introduced the moderate mission concept and two missions that would fit into this mission category, the Submillimeter Imager and Line Survey (3.65 m diameter aperture) and the Submillimeter Intermediate Mission were studied. Mission studies continued into the early '90s but died out by the end of 1994. NASA activity in the submillimeter area continued, after 1994, through the support of instrument development, which was necessary for other NASA missions, and light-weight mirror development through small business innovative research (SBIR) contracts with industry.

ESA's 8 m aperture FIRST concept was accepted as part of ESA's Horizon 2000 plan. It was soon descoped to a 4.5 m aperture and eventually to a 3 m diameter reflector before increasing to its current 3.5 m diameter in early 1997. FIRST was chosen as ESA's 4th cornerstone mission in November 1993. During this period, with budgets being tight, astronomers at the 1990 Liège symposium recommended that NASA and ESA combine resources for a joint mission. This did not come about until 1997 when NASA indicated interest in joining ESA as a junior partner in the FIRST mission. Besides contributing to 2 of the 3 instruments NASA was interested in delivering a telescope to ESA. NASA funding for this effort first arrived in early 1998.

## 3. TELESCOPE REQUIREMENTS

The telescope requirements are driven by the need to be diffraction limited at 80 μm. The most important requirements that characterize the telescope are listed in Table 1. The design must be a simple 2 mirror telescope, either a Cassegrain or a Ritchey-Chretian. We have chosen the latter.

Table 1. Key Telescope Requirements

| | |
|---|---|
| Bandwidth | 80 - 670 μm |
| Telescope wavefront error (WFE) | ≤10 μm rms., ≤6 μm rms. goal |
| Diameter | 3.5 m |
| Focal Length of primary | 1.75 m |
| System focal length | 28.50 m |
| System f number | 8.68 |
| Field of view | ± 0.25° |
| Surface roughness | ≤0.6 μm rms. |
| Operating temperature | 70 to 90 K |
| Relative spectral transmission | ≥97% at delivery of telescope |
| Mass | 260 kg |

The 6 μm rms. goal is driven by the PACS instrument which desires diffraction limited operation at 80 μm (the shortest wavelength for HIFI is 111 μm and for SPIRE is 200 μm). Due to the mass requirement and the 20 K operating range we selected an all CFRP primary mirror and structure (the secondary mirror will be made out of Zerodur). A mass breakdown is given in Table 2.

Table 2. Telescope Mass Breakdown

| | Mass (kg) |
|---|---|
| Primary mirror | 113 |
| Secondary mirror | 6 |
| Tripod support for secondary mirror | 10 |
| Telescope triangle | 10 |
| Thermal blanket and heater plane | 16 |
| Contingency 15% | 23 |
| Total | 178 |

The maximum areal density of the primary mirror, assuming that the mass of all the other components do not change, from those in Table 2, can be no higher than 19.5 kg/m$^2$ before the mass budget is violated. Areal densities this high might allow other materials, such as SiC and Be, to be used for the primary. When estimating the mass of a telescope made from these materials, the scaling of the areal density with diameter must be carefully considered. Simply using areal density values for mirrors in the 1 m diameter range, without taking into account the diameter scale factor might lead to a low estimate for the mass of the FIRST telescope. Fracture toughness was another consideration in the choice of CFRP over SiC or Be. (The fracture toughness of SiC is comparable to that of glass and 10% to 20% that of Be. The fracture toughness of Be is roughly 25% that of aluminum. For CFRP the fracture toughness is less of an issue than the strength of adhered joints.) Thermal considerations will be considered in the next section.

## 4. COMPOSITE MIRROR TECHNOLOGY DEVELOPMENT

During the LDR mission analysis period it was realized that to put a 20 m diameter glass mirror in orbit would be prohibitively expensive. Light weight mirrors were necessary. Furthermore the original orbits considered for LDR and the smaller submillimeter missions were planned for either low or high earth orbit. In either case the thermal gradients on the mirror could cause a substantial distortion and the best way of mitigating this problem was with low CTE material. Furthermore if the CTE was sufficiently low the room temperature shape of the mirror would change little when reduced to the operating temperature. The estimated operating temperature for an earth orbiting, passively cooled telescope is 160 K. Thus a reasonable choice for a lightweight, low CTE mirror material was CFRP.

To respond to the technical needs of LDR, NASA established the Precision Segmented Reflector (PSR) program in 1988. The objectives were to develop lightweight mirrors and the technique to align and phase 1 to 2 m diameter mirror segments on a lightweight structure. Both JPL and Langley Research Center (LaRC) were funded by NASA to support this program. With PSR funding, JPL set up a working relationship with Hexcel to design and fabricate CFRP mirrors. This relationship continued into 1992 and produced 1 m size mirrors with at best a 1.2 μm rms. surface error at room temperature that typically showed a 3 μm rms. change when dropped in temperature by 120°C. Areal densities of these mirrors were in the 5 to 8 kg/m$^2$ range.

Before the start of the PSR program both Dornier and MAN were making substantial progress in CFRP mirror development. MAN mirrors were eventually used for the 2 m diameter PRONAOS balloon-borne observatory. In the late '80s COI, Space Systems/Loral and Hercules Aerospace Company began to develop CFRP mirrors. Towards the end of the PSR program COI built two 0.5 m diameter mirrors as a demonstration of their capability. In 1992 following the end of the mirror development phase of the PSR program, COI continued their mirror development activities with NASA SBIR and internal R&D funds.

With SBIR funding, through Marshall Space Flight Center (MSFC), COI first worked on improving the thermal stability of CFRP mirrors, which were then at roughly 2.5 μm rms. per 100°C drop in temperature. In the 1993 to 1995 time period COI developed a new core design that resulted in less than 0.5 μm rms. figure change over a 80°C temperature drop. This effort was followed by the development of a prototype mirror for the Microwave Limb Sounder (MLS), also with NASA SBIR funds. Completed in late 1996, it is an off-axis reflector with an elliptical footprint of 1.6 m x 0.8 m (1 m$^2$ area). The MLS flight mirror, completed in the last year, had an rms. surface error of 4.5 μm as did the prototype mirror.

In the spring of 1997, when NASA indicated an interest in becoming a junior partner to ESA, NASA turned the telescope responsibility to JPL. The first question for JPL to answer was what was the best material to use for the telescope? Knowing that ESA wanted a telescope without active correction capability, JPL felt that no matter what material would be used technology development would be needed. Not having the time or the resources for a telescope material trade study but having had good experience with the CFRP development work at COI, JPL decided that the material with the least risk was CFRP. Much of this decision was based on the 0.5 m diameter thermally stable mirrors and the MLS mirror all built by COI (see Figure 3). By June 1998 COI was on contract to develop the mirror technology for the FIRST telescope.

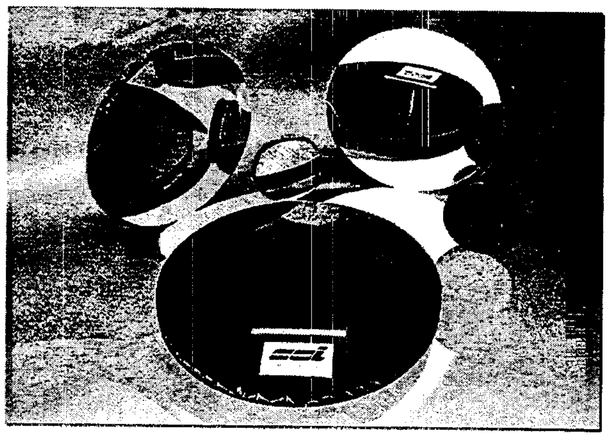

Figure 3a. COI MSFC Thermally Stable Mirrors

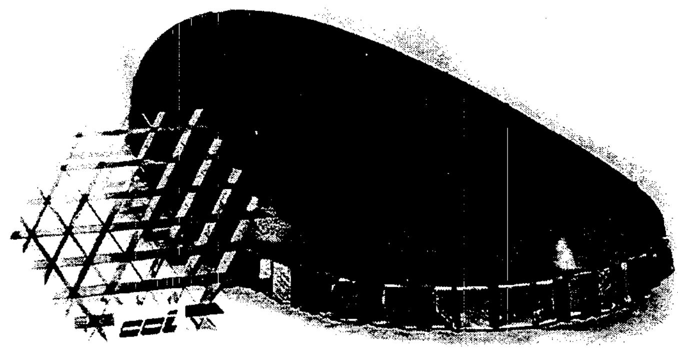

Figure 3b. COI MLS Prototype Mirror

Other considerations that entered our decision in choosing CFRP were the mass and fracture toughness, mentioned in section 3, and the CTE. Figure 4 shows the CTE as a function of temperature for various materials. Due to the 20 K operating range and the f/# of the primary, a ±10°C change in temperature with a material of CTE greater than 0.6 ppm/°C would cause more than a 1 μm WFE, assuming that the structure, secondary attachment and secondary were not made of the same material. Another important parameter is the total strain from room temperature to the operating temperature, which is shown in Figure 5 for CFRP and SiC. This parameter would not be a concern if the telescope was made of one homologous material. The last critical parameter is the uniformity of the material. Admittedly this is a problem with CFRP but with new processing the material used by COI shows a strain variability of no more than 20 ppm over a 220°C drop in temperature. A material variability of 30 ppm, over this temperature range, is more than adequate for the FIRST telescope, due to the unique design[5,6].

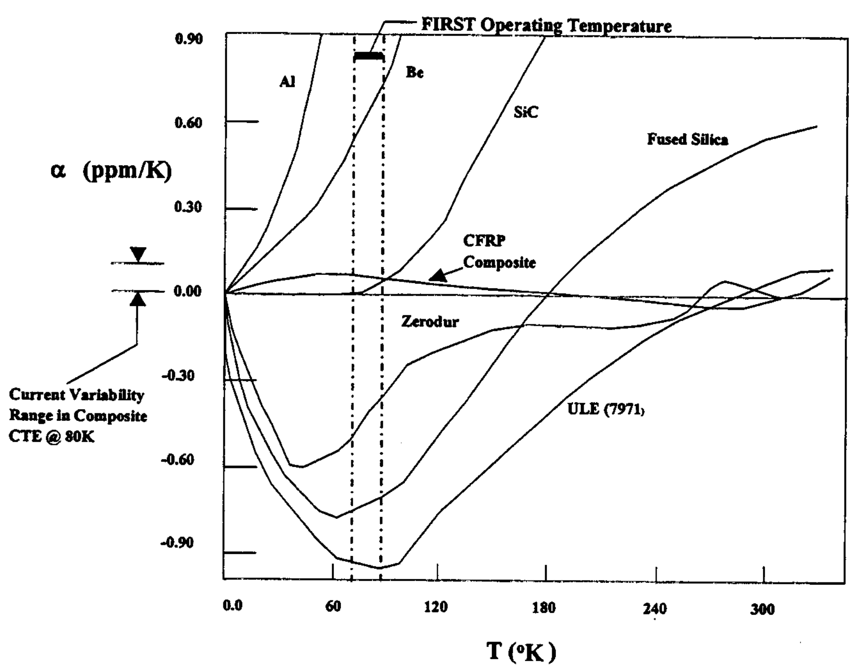


Figure 4. Thermal Expansion Curves of Selected Mirror Materials

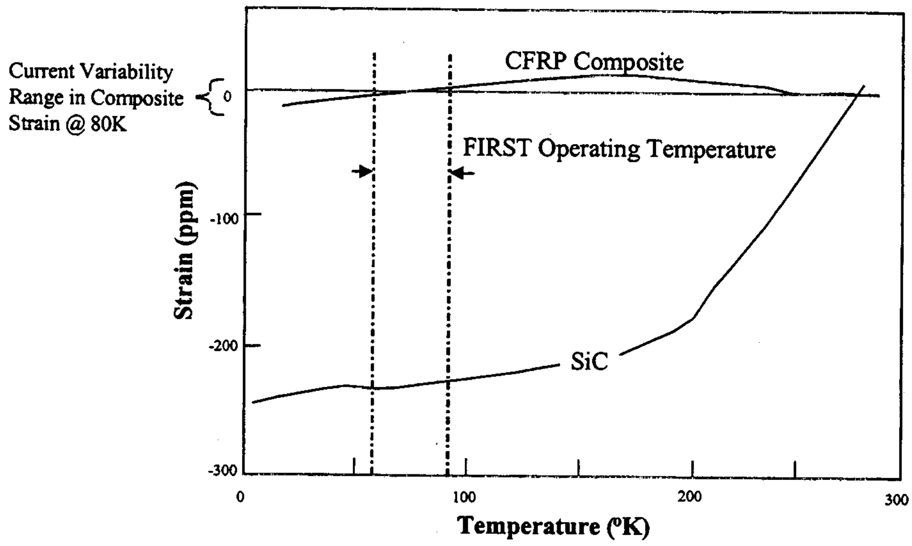


Figure 5. Thermal Strains of CFRP Composite and SiC Materials Upon Cool-Down to Cryogenic Temperatures

At the inception of the COI contract it was clear to JPL and COI that COI's first task was mirror technology. FIRST's primary mirror, with an area of 9.55 m$^2$, will be 9.5 times larger than the MLS mirror, will operate between 70 and 90 K, nominally 215°C below room temperature, and needs a lower surface error than MLS. The thermally stable mirrors made by COI are 58 times smaller than the FIRST primary will be and were only tested to 120 K. If COI and JPL considered these mirrors as the state of the art with CFRP then more development was needed to meet the FIRST requirements. Just so that we do not make this effort seem completely impossible be aware that some of the MLS mirror's surface error could be explained by the 2.3 μm rms. accuracy of the mold and the variable thickness of the release film (not used for the FIRST mirror) but this still leaves over 3 μm rms. of surface error at room temperature. Clearly the initial part of our telescope development effort had to be to develop the CFRP mirror technology required for FIRST.

## 5. WFE AND ERROR MITIGATION

The WFE budget is given in Figure 6. The largest errors in the budget are the cool down, dry out and as manufactured error. If we go one more level down in the error budget we will discover that these errors are due to material variability both in CTE and coefficient of moisture expansion (CME). There are several ways of dealing with these errors and they are discussed below.

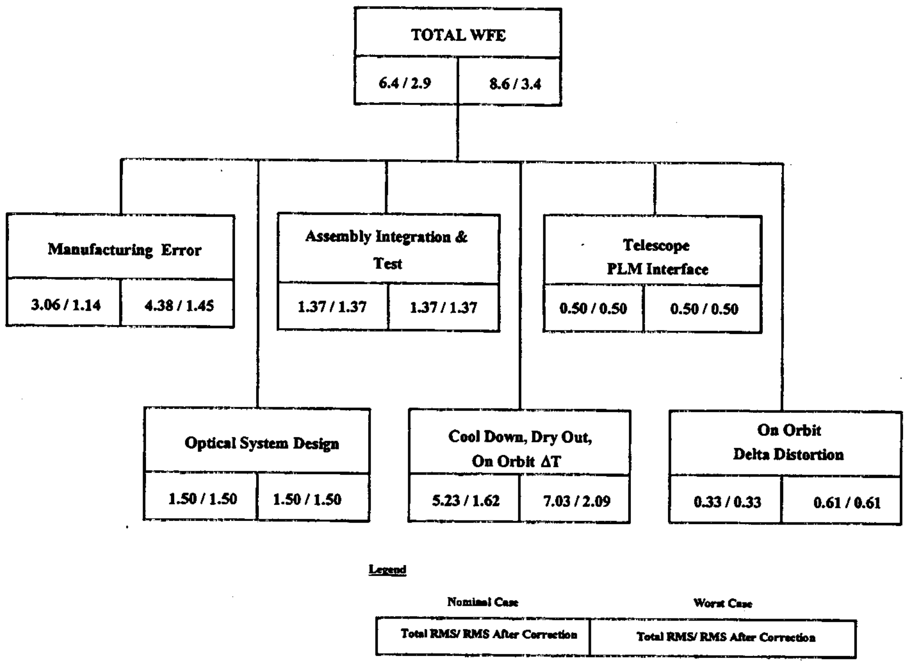


Figure 6. FIRST Telescope WFE

**5.1. Correction of Low Spatial Frequency Errors**

Due to material variability a small astigmatism tends to appear in a composite mirror. Typically this astigmatism increases as the mirror is cooled to its operational temperature. Our plan is to correct astigmatism and other low order spatial frequency errors in the primary mirror by figuring the secondary mirror. Most likely this technique is limited by how accurately the low spatial frequency errors can be measured.

**5.2. Moisture Effect**

The resin used for the mirror is a cyanate which typically absorbs moisture. Though cyanate CMEs (~ 105 ppm/% moisture by weight for the material used for primary mirror) are comparable to epoxy CMEs they absorb one-fifth as much as epoxies and furthermore their absorption and desorption rates are at least ten times faster than epoxies. Absorption rates are the same as the desorption rates. In roughly 9 days a 2 mm-thick laminate can reach 80% of its saturated moisture uptake.

Our plan is to keep all CFRP parts bagged with a positive flow of $N_2$ applied. Moisture absorbed when the mirror is exposed for fabrication or testing can be desorbed when the mirror is bagged. After launch the telescope is required to be baked out for the purpose of desorbing contaminants that result from spacecraft outgassing and hydrazine plume back-scatter. This bakeout will also dry out any residual moisture in the CFRP. If we assume that after bakeout the telescope will be free of moisture then we must be sure that in this state the telescope meets the WFE budget. We can be reasonably sure of this if the telescope is always tested and adjusted before launch when it is in a dried out state. Since it is not certain that the telescope will be tested in a completely dried out condition and since there is the possibility that the in orbit bakeout will not be perfect we have allowed for a residual moisture level of 25% by weight of the saturated moisture level (this is the saturation level for the atmospheric condition of 95% relative humidity, RH). A 0.4 μm rms. WFE, which is a small part of the WFE budget, is associated with this level of moisture. Figure 7 shows the dependence on time and temperature for drying out a 2 mm-thick CFRP coupon. If the bake out process is carried out at 70°C, it takes less than 2 days for the composite to dry-out from near saturation to 25% of it saturated state at 95% RH.

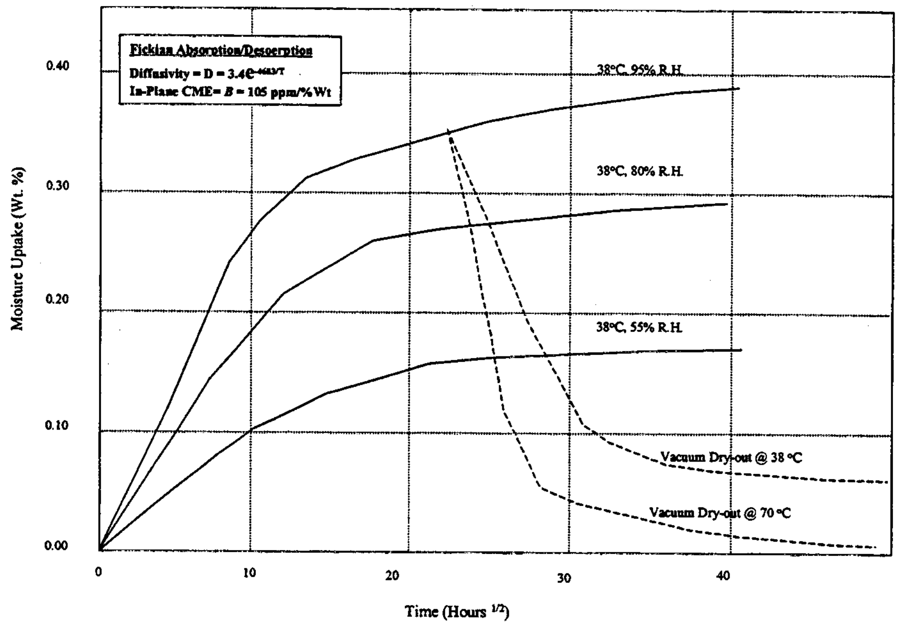


Figure 7. Moisture Absorption/Desorption Curves for 2 mm-thick CFRP Composite Laminates at Different RHs. The curve also shows that if the composite was exposed to 95% RH at 38°C for 500 hours it reaches a %moisture level of 0.35%. If the composite is then baked out for less than 2 days at 70°C its %moisture level drops below 25% of its saturated level.

### 5.3. Active Secondary Mirror Control

An actuated secondary mirror will be used when testing the telescope in the thermal vacuum chamber. When the mirror enters the thermal vacuum test for the first time the primary to secondary mirror spacing will only be known to several mm. With actuators the spacing can be adjusted to an accuracy of roughly 5 μm without warming up the telescope. It is not yet known if actuators will be needed in flight. Having actuators in flight will reduce the risk of unanticipated mirror distortions ruining the mission. On the negative side are the risk of an actuator failure and the cost of implementing this system.

## 6. CONFIGURATION

The telescope to spacecraft interface are the points where three bipods attach the telescope support structure to a girth ring around the cryostat (see Figure 8a). This interface is 250 mm below the vertex of the primary mirror and 800.2 mm above the best on axis focus. This places the telescope interface 30.8 mm below the top of the payload module (PLM) cavity. (Within the PLM cavity is the cover to the cryostat.) From the top of the PLM cavity to the bottom of the primary mirror there is a 19 mm gap. Mirror thickness will be 203.2 mm and the distance from the best on axis focus to the vertex of the primary is 1,050.2 mm.

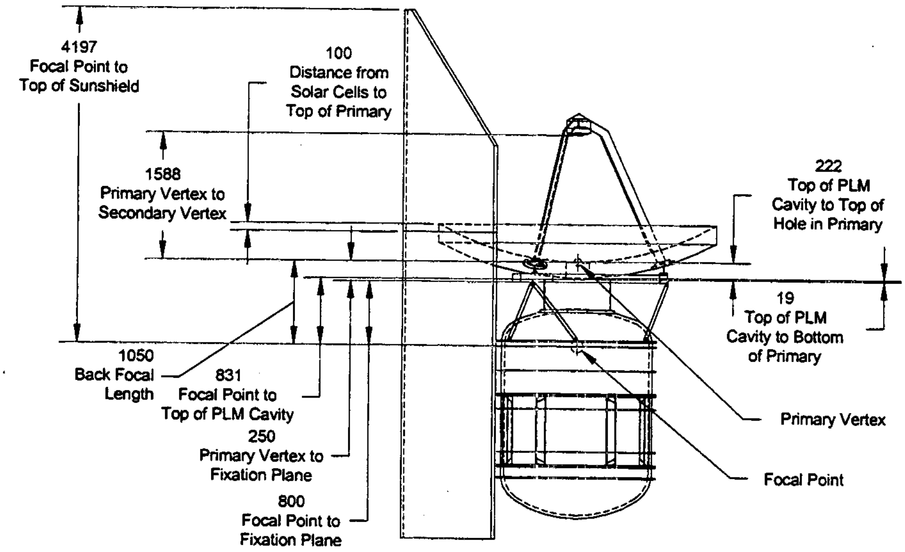


Figure 8a Telescope, Sunshade and PLM (all units in mm)

The telescope support structure is just a triangle that interfaces the bipod attach points to the primary mirror mounting points via flexures. These mounting pads are at a radial distance of roughly 1.1 m from the optical axis and are attached to the primary mirror's core near the back facesheet. A tripod supports the secondary mirror assembly and the legs of the tripod connect to the primary mirror's mounting pads but not directly to the primary mirror.

Stray light issues have impacted the design of the tripod legs. The source of the stray light is the sunshade. Emission from the sunshade can scatter off of the edge of the tripod leg facing the optical axis but only if this edge has a view of the sunshade. Thus by placing two legs on the sun side of the telescope only the one leg on the anti-sun side can scatter radiation into the focal plane. To further reduce this scattered radiation a v-shaped spoiler, placed on the edge of the tripod leg facing the optical axis scatters the emission from the sunshade to cold space. Each leg obscures the plane wave incident on the primary and the spherical wave reflected from the primary to the secondary. The latter effect can cause significant obscuration and there are two ways of reducing this. One way is to simply place the leg beyond the edge of primary but the penalty would be that the structure to support the axial loading during launch would be massive and complicated (note that the vertical distance from the edge of the primary to the edge of the secondary is 1,184 mm so the rise angle made by the leg with respect to the horizontal plane would be 34°). If for structural reasons the tripod legs need to pass through the primary mirror, then the closer the legs are to the edge of the primary and the closer that their rise angle is to 90° the lower the obscuration of the spherical wave. We have increased the rise angle of the tripod legs to the maximum allowed by the mechanical designers. With one bend in the tripod leg on the anti-sun side, this leg would be exposed to sunlight when the telescope is tilted 30° towards the sun. Figure 8b shows that an extra bend has been added to this leg to avoid the sun exposure problem. This figure also shows that the amount of clearance to the sun's rays is small and allows little room for actuators. At this time we have not determined if this will be a problem.

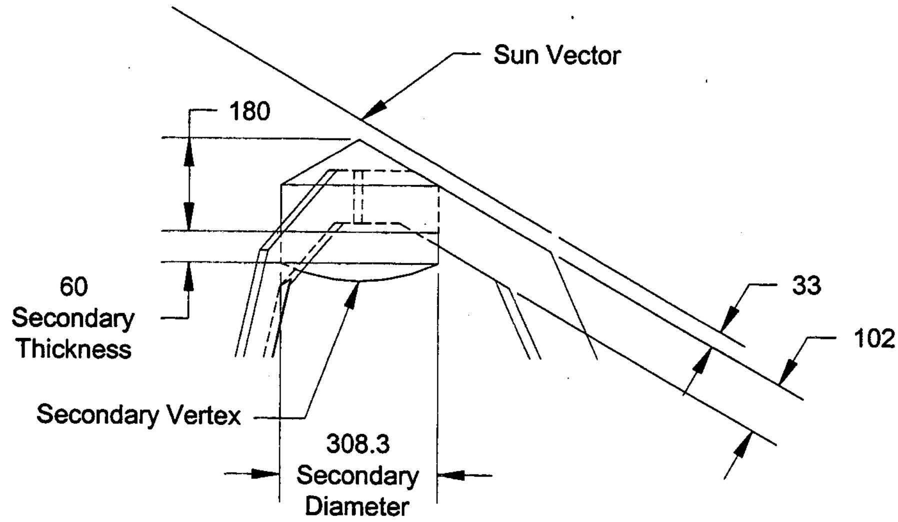


Figure 8b. Tripod Leg With Two Bends to Avoid Sun (all units in mm)

## 7. THERMAL

The telescope has an excellent view factor to cold space. Heat sources on the primary are from the sunshade, sunshield and the spacecraft bus. The sunshield is the part of the sunshade that has solar cells mounted on the side facing the sun and as a result the side facing the PLM is estimated to be at 250 K. Without solar cells the sunshade temperature on the side facing the telescope is estimated to be 173 K. Thermal energy from the sunshield and spacecraft bus are greatly reduced by a multi-layer insulation (MLI) blanket covering the bottom of the primary mirror. Since the sunshield ends 100 mm below the edge of the primary mirror its influence is only through the MLI blanket which has an effective emissivity of less than 0.015. Figure 9 shows the temperatures of the sunshade and mirror. This model assumes 0.02 emissivity for the primary and secondary mirrors and the tripod and 0.05 for the sunshade and sunshield.

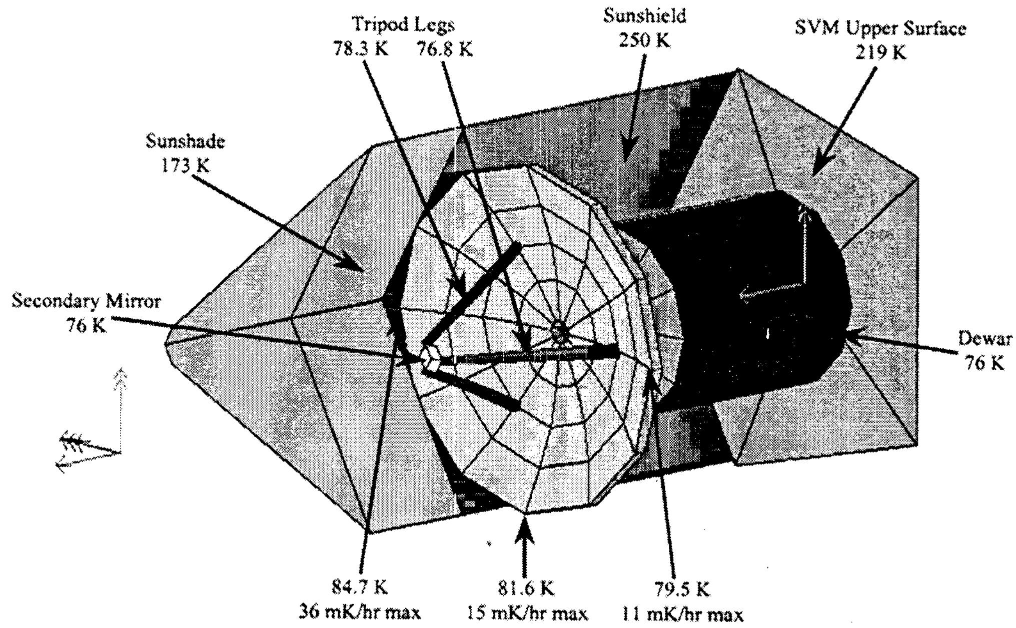


Figure 9. Telescope and Sunshade Temperatures when the Telescope is not Tilted Toward the Sun. Maximum thermal gradients for 3 points on the primary following a 30° tilt towards or away from the sun.

Primary mirror temperatures and temporal gradients, for 3 points around the edge, are shown in Table 3. The z-axis is parallel to the vector drawn from the sunshade spine to the single strut on the anti-sun side of the primary mirror and the y-axis is perpendicular to the z-axis and in the plane of the primary mirror's aperture. The 30° tilt reduces the heat load from the sun and the maximum rate that the temperature decreases, following this tilt, is given in the last column of Table 3.

Table 3. Primary Mirror Temperatures and Temporal Gradients for Three Points Around the Edge of the Mirror.

| Thermal Node | T(K) with no tilt | T(K) with 30° tilt | Maximum Temporal gradient (mK/hour) |
|---|---|---|---|
| Edge near sunshade | 84.7 | 82.2 | 36 |
| Edge facing cold space | 79.5 | 77.6 | 10.8 |
| Edge on y-axis | 81.6 | 79.5 | 13.2 |
| Gradient along sun vector | 5.1 | 4.6 | 34 |
| Average mirror temperature | 82.1 | 80.0 | |

First note that the average telescope temperature drops by only 2.1 K when the telescope is tilted by 30° with respect to the sun vector. Maximum spatial gradient along the sun vector is required to be below 10 K and is easily met by roughly a factor of 2. Maximum spatial gradient along the y-axis is required to be below 1 K and the largest gradient of 0.05 K will occur only when the telescope is allowed its maximum roll (about the x-axis) of 5°. The temporal gradient along the z-axis is required to be less than 780 mK/hour and along the y-axis less than 78 mK/hour. Both requirements are met by over a factor of 20.

Decontamination heaters are required to raise the temperature of the telescope to a minimum of 313 K, in orbit. The current plan is to set up a heater plane, offset from the back of the mirror, that would radiatively heat the mirror. These heaters will be mounted on the side of the 50 layer MLI blanket facing the back side of the primary mirror. Both the heater plane and the MLI blanket will be held off the back of the primary mirror with the same support system. Analysis predicts primary mirror temperatures that spatially vary between 327 and 345 K when 600 W are applied to the heaters.

## 8. CONCLUSIONS

An all composite version of the FIRST telescope has been designed and thermal and mechanical requirements are met.

## ACKNOWLEDGMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The following people at JPL have supported the work in this paper; Tom Borden with discussions on the FIRST program and in assembling the paper, Larry Scherr for stray light analysis and Paul Willis with discussions on CFRP technology. Terry Cafferty, of TC Technology, advised on the thermal analysis. Dustin Crumb, of Swales Aerospace produced configuration drawings. Dan Barber and Roger Johnston of LightWorks Optics Incorporated, performed optical design and analysis. Ed Freniere, of Lambda Research Corporation, supported the stray light analysis. The following people at COI have supported the work in this paper; Dave Berardelli with optomechanical design, Randy Clark with mirror development activities, Mary Fisher with assembling the paper, John Richer with optomechanical design, Dave Sheikh with mirror development activities, and Anthony Tam with configuration drawings.

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