Structural design challenges for a Shuttle-launched Space Interferometry Mission

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ABSTRACT

The Precision Structure Subsystem (PSS) for the Space Interferometry Mission (SIM) is a large composite structure designed to house the interferometer optics in a structurally stable and thermally benign environment on orbit. The design requirements of the PSS as a shelter for the optics must be weighed against the demands of the baseline launch vehicle: the Space Shuttle. While a Shuttle launch provides new opportunities for the mission, it also presents new challenges. Many of these challenges are reflected in the design of the PSS:

- Structural stability for supporting the optics on orbit
- Interface to the launch vehicle, including acoustic and stress loads for the launch environment
- Minimization of launch mass to provide maximum payload to orbit for the science mission
- Thermal control to achieve necessary structural stability and a stable thermal environment for the optics
- Dynamics isolation from jitter sources and microdynamics effects

Many of these design challenges result in inherently conflicting requirements on the design of the PSS. TRW, drawing on our experience with large composite structures such as the Chandra X-ray Observatory, has created a conceptual design for this structure that addresses these challenging requirements. This paper will describe the conceptual design of the PSS including the trades and analyses that led to this design.

Keywords: composite structures, jitter isolation, SIM, precision structures, space interferometry

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1. INTRODUCTION

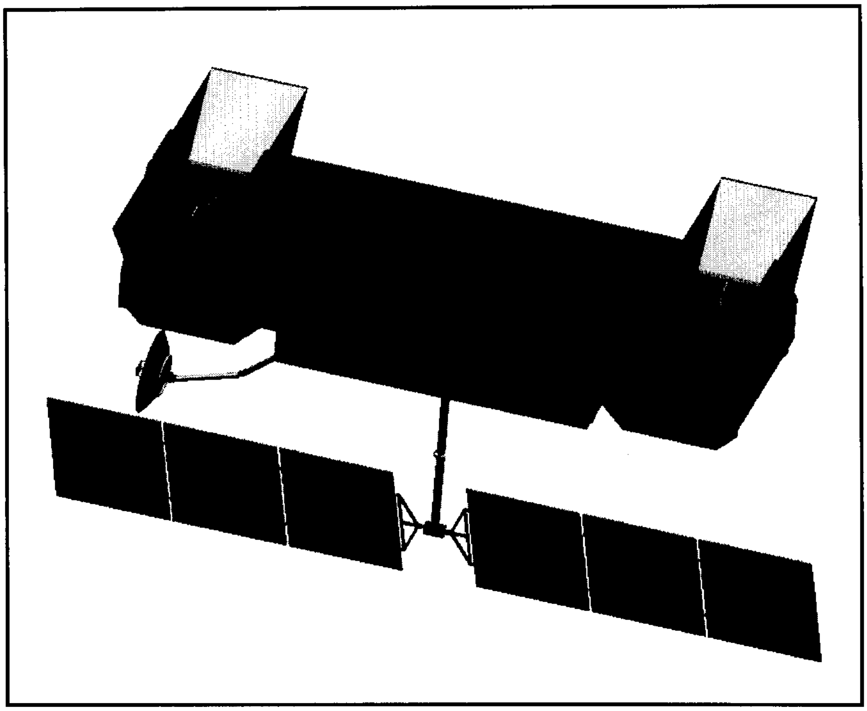


Figure 1—The SIM Flight System

The Space Interferometry Mission (SIM) is a member of NASA's Origins program. It grew out of the 1991 *Decade Survey on Astronomy and Astrophysics*[1], which called for a space-based astrometric interferometry mission with performance goals well beyond the then-current state of the art. SIM is being managed for NASA by the Jet Propulsion Laboratory, which is also responsible for overall system engineering and for the instrument control electronics. In partnership with JPL are TRW, responsible for the spacecraft, the precision structure and ATLO (Assembly, Test and Launch Operation); Lockheed Martin, responsible for the instrument optics and overall instrument integration and test; the California Institute of Technology, which houses the Interferometer Science Center; and a team of 15 project scientists.

The SIM Flight System, shown in an artist's conception in Figure 1, consists of four Michelson stellar interferometers. Two of the interferometers are the science interferometers, with 10-meter baselines. They operate as fully redundant systems, with only one operational at a time. The other two interferometers are the guide interferometers, with an 8.5-meter baseline. Both guide interferometers are operational during science data collection.

The Precision Structure Subsystem (PSS), the structure of interest in this paper, is the long, house-like structure in Figure 1. It is a composite structure that houses all of the optics for the interferometers. Openings at either end of the structure allow the collector optics to view space. The remainder of the interferometer optics is under the "roof" in the center of the structure. The wedge-shaped structures surrounding the openings serve a dual role. During launch operations they are closed and serve as a contamination cover for the optics. Once on orbit they deploy and become sun shields. Operationally the Sun is kept below the plane formed by the tops of the sun shields.

Attached below the PSS is a rectangular structure known as the backpack. The backpack contains most of the electronics associated with both the normal spacecraft housekeeping and control functions as well as those associated with real-time control of the interferometer optics. The backpack is dynamically and thermally isolated from the PSS to minimize thermal and dynamic disturbances during science data collection. A high-gain antenna and a solar array are attached to the backpack.

The baseline launch system for SIM, which will fly in an Earth-trailing solar orbit, is the Space Shuttle augmented by a bi-propellant liquid upper stage that will boost SIM from the Shuttle orbit to its final orbit over about a week's time. The upper stage, known as the Integral Propulsion Module (IPM), has direct heritage to the integral propulsion system that TRW developed for the Chandra X-ray Observatory.

SIM's basic mission, outlined in the *Decade Survey*, is to measure the position of stellar objects down to magnitude 20 to an accuracy more that 100 times what has been previously possible (wide angle astrometry). Its mission is also to look for evidence of planets at about three earth masses around nearby stars as an enabler of follow-on programs such as Terrestrial Planet Finder (narrow angle astrometry).

Figure 2 is a schematic representation of a Michelson interferometer such as those used on SIM. The measurement of interest for stellar astrometry is the angle θ. To meet the demands of the *Decade Survey*, this angle needs to be determined to within a few microarcseconds. At this level of accuracy it cannot be measured directly by, say, reading out gimbal angles. It is determined indirectly by measuring the external path delay and the interferometer baseline and computing θ. The external path delay is actually determined by measuring the internal path delay once fringes are formed on the fringe detector. To find θ to within a few microarcseconds, the internal path delay and the baseline must be measured—via interferometer metrology—to less than a nanometer.

Also of interest for astrometric applications is the orientation of the baseline in inertial space. That is the purpose of the guide interferometers: to hold the baseline fixed relative to known stars to within a few microarcseconds.

The PSS provides a structurally, dynamically and thermally stable environment so that the interferometer optics can achieve these ambitious goals.

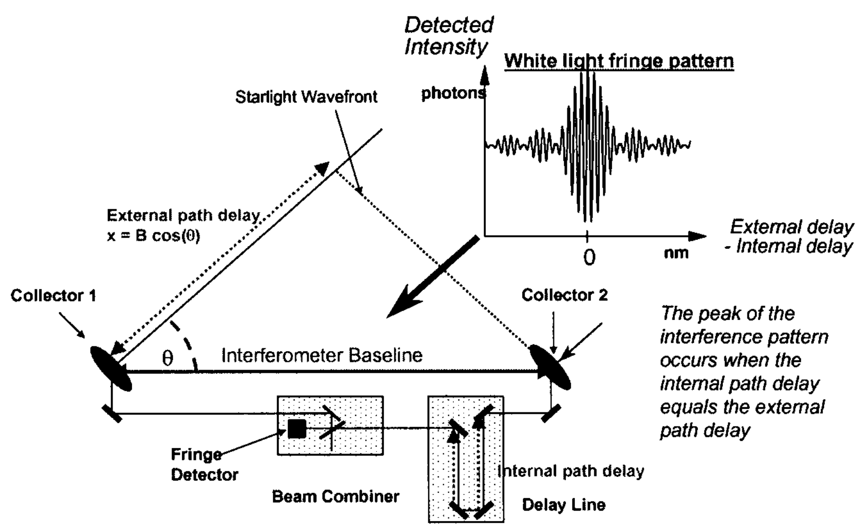


Figure 2—Michelson Stellar Interferometer

A Note on SIM Classic. Several times in this paper reference will be made to a previous configuration of SIM known as "SIM Classic." From the point of view of PSS design, SIM Classic was composed of a deployable structure that included two 1m x 2m x 5.5 m "wings" that housed the interferometer optics and a 9 m-long deployable boom that contained most of the external metrology equipment. During initial activation the "wings" unfolded and latched together to form the interferometer while the metrology boom deployed roughly orthogonal to the wings to establish the external metrology system. Considered a high-risk configuration, this design was revised through late 2000 and 2001 into the current configuration known generically as “shared baseline.” The availability of the large payload bay in the Space Shuttle made consideration of this non-deployable (“monolithic”) structure possible.

2. REQUIREMENTS

Requirements for the PSS begin at the top. The requirements for pointing accuracy of SIM flow down all the way from the *Decade Survey* and are specified in terms of absolute knowledge of star positions at the end of a 5-year mission:

- For wide-angle astrometry, examining stars down to magnitude 20: 4 microarcseconds (1 σ RMS).
- For narrow-angle astrometry, where relatively bright, nearby stars are of principal interest: 1 microarcsecond (1 σ RMS).

As was mentioned earlier, these requirements translate into requirements for determining the length of the baseline and the internal path delay. The 1 microarcsecond requirement implies a knowledge of these distances to within about 50 picometers. To achieve this level of accuracy, a number of tricks of the trade are employed including averaging out random errors over multiple observations of the same star over the life of the mission. However, they clearly remain extremely challenging requirements. The general approach to meeting them on SIM has been to do it in layers:

- The spacecraft attitude control system points the instrument to an accuracy of a few arc seconds so that the guide interferometers can acquire the guide stars and track the orientation of the baseline with respect to the guide stars to within a few microarcseconds.
- The PSS structure is designed to be stable to within a few microns so that the metrology beams do not walk on the optics, and so that the high-resolution mirror control can take out other motion
- The temperature control of the PSS is such that a very stable environment is provided for the optics such that further optics thermal control can achieve stabilities in the milli-Kelvin range.
- Vibration isolation is achieved in at least two steps: first the isolation of the backpack from the PSS to attenuate any vibration arising in the backpack, then filters take vibration out of fringe tracking controllers. A third layer of isolation exists for the reaction wheels, which are the major source of jitter on the spacecraft.

The requirements that flow to the PSS emerge principally from the astrometric error budget and the dynamics and control error budget:

- <u>Position stability</u>. This specifies the relative motion of parts of the structure as a function of time. It applies to the structure as a whole, but more importantly to the mounting positions of the optics.
  - $< 1\ \mu m$ (1 σ RMS) for 5 min.
  - $< 10\ \mu m$ (1 σ RMS) for 1 hour

- <u>Alignment stability</u>. This addresses the relative alignment between guide and science collector optics. In the current design concepts for optics mounting this requirement may be modified or eliminated as far as the PSS is concerned.
  - < 4.2 milliarcseconds (1 σ RMS) for 5 min.

- <u>Relative dynamic stability</u>. Given the stable structure defined by the above requirements, vibration sources need to be controlled such that fringes are clear and stable on the detectors. The basic vibration rejection requirements are the following:
  - During fringe tracking, ±5 nm (1 σ RMS) above 100 Hz
  - During fringe acquisition, ±40 nm (1 σ RMS) above 100 Hz

  The details of the dynamic stability requirements below 100 Hz are addressed in the section below on dynamics.

- <u>Thermal control</u>. Part of our thermal control requirements derive from the position stability requirements above. However, there remains a requirement to control the environment of the optics enclosures within the PSS so that the thermal control of the optics can achieve the required milli-Kelvin stability levels.
  - Temperature stability ±0.1°C for one hour

  Nominal setpoint for the optics enclosures is 20°C, however, the absolute temperature of the enclosure is less important than its stability. The setpoint may vary over the life of the mission **as will be discussed below**.

The above requirements result in three major areas of emphasis as far as the structural design of the PSS is concerned:

- Stability of structure while also minimizing structure weight to fit within the constraints of a Shuttle launch
- Isolation of vibration sources from the optics

- Providing a benign thermal environment to minimize CTE effects in structure and give the optics a comfortable environment in which to achieve milli-Kelvin temperature control.

These issues will be discussed in detail below.

3. STRUCTURAL STABILITY

Figure 3.1 shows the PSS structure with parts of the outer layers removed so that interior structural details can be seen. The bays on either end of the structure hold the collector and compressor optics for both the science and guide interferometers. The large mirror seen in the far left corner of the left-hand optics bay is a science siderostat. It is gimbaled and is the primary collection optic for the science interferometer. Its companion siderostat is hidden behind the right-hand end bulkhead. The distance between the centers of these two mirrors define the science baseline of 10 meters. The redundant science siderostats are hidden behind the near side walls of the optics bays. Between the primary and redundant siderostats are the primary compressor mirrors. Visible in the right optics bay are some of the optics elements of the guide interferometers. The round corner cube seen near the apex of the "roofline" defines one end of the guide interferometer baseline and also defines the height of the PSS structure. An identical pair of guide interferometer optics is hidden behind the bulkhead in the left-hand optics bay. In the center section of the PSS are the four astrometric beam combiners (the box-like structures) and the delay lines and relay optics (to the right of the ABCs). For details of the optics configuration and design, refer to Stubbs, et al[2].

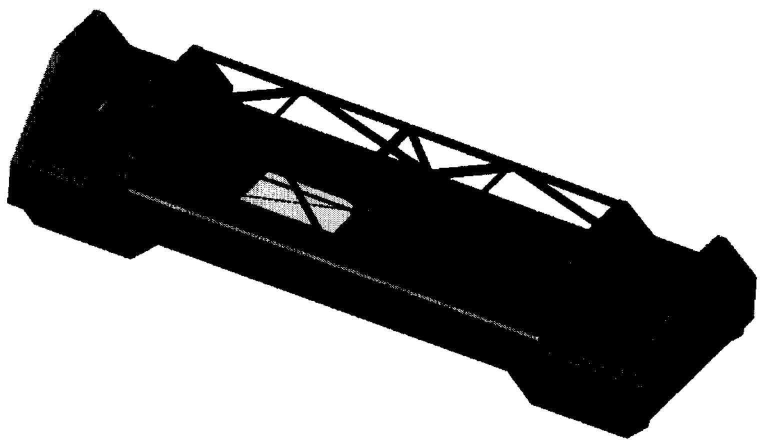


Figure 3.1—Cut-away view of the SIM precision structure

The basic PSS structure is a rigid platform upon which the interferometer optics are mounted. The width of the platform is dictated by two conflicting requirements: The separation distance between the primary and redundant science siderostats that necessitates a PSS width of 3.8 meters in the area of the optics bays; and the accommodations requirements of the Space Shuttle that force a narrowing of the structure to 3.2 meters to allow room for support cradles that will attach SIM to the Shuttle payload bay (see the section on Shuttle accommodations below).

The roof-like structure in the center serves three purposes. It helps stiffen the PSS structure during Shuttle launch and abort landing operations; it provides a protective shield for the metrology beams that criss-cross the center of the PSS structure; and it provides a mounting surface for radiators required to cool CCDs in the astrometric beam combiners.

A final feature of the PSS configuration is the extension of the side panels of the center section below the siderostat bay structures in a cradle-like arrangement. The extension was necessitated by the naturally weak right-angle corner where the narrow center section meets the wider optics bays. In addition to the stringent stability requirements at the mounting points of the key instrument optics, these extensions will help support the almost 500 kg of optics and support structure during the launch environment.

The structural stability requirements for the PSS dictate the following design requirements:

- On-orbit structural stiffness > 12 Hz
- CTE < 10^{-7}
- Damping < 1%

The requirements of a Shuttle launch place additional constraints on the PSS design, especially in the area of structural design criteria and fracture mechanics. However the influence of the Shuttle launch environment has been minimized by designing Shuttle attach points in such a way that the PSS is primarily an optical support structure not a primary load path during launch operations.

Due to the stringent SIM on-orbit thermal and structural dynamic constraints and the demanding launch environment, the PSS design employs the "isogrid" design concept fabricated using high specific modulus and near-zero CTE graphite fiber reinforced plastic (GFRP). The isogrid design, developed by Dr. R. R. Meyer[3], is an integral stiffened waffle with a pattern of 60° triangles. This concept is based on the simple fact that triangular trusses are efficient structures and its geometric pattern makes the structure act like an isotropic material. The isogrid pattern is schematically shown in Figure 3.2. ??

Many isogrid structures that are primarily applicable to panel construction consist of 60° equilateral triangle ribs with attached skin. There are three types of isogrid panel designs that can be tailored to meet the PSS strength and stiffness requirements. They are:

- Flanged isogrid. As seen in Figure 3.3, this design is used for structures that are highly loaded and stiffness critical. Its cross-section has an I-beam form with a flange to provide the added strength and stiffness.
- Unflanged isogrid. Figure 3.4 shows an unflanged isogrid. It has a cross-section in the shape of an inverted T. This design may be used when the loads and the stiffness requirements are moderately low. For non-structural members, the spacing of the ribs attached to skin may be increased to reduce weight.
- Open isogrid. Both flanged and unflanged isogrid skins are removed as shown in Figure 3.5. The skin cutouts are best suited when local access is required.

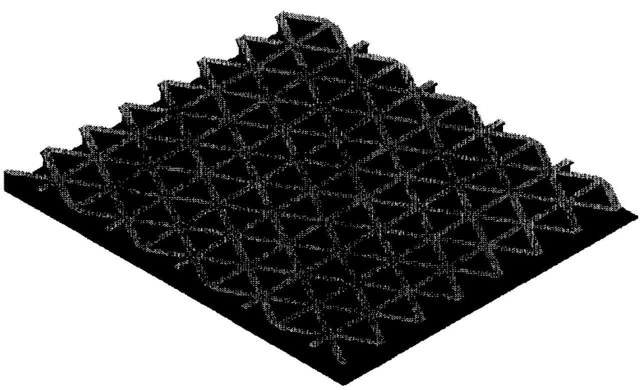


Figure 3.2—Flanged isogrid construction

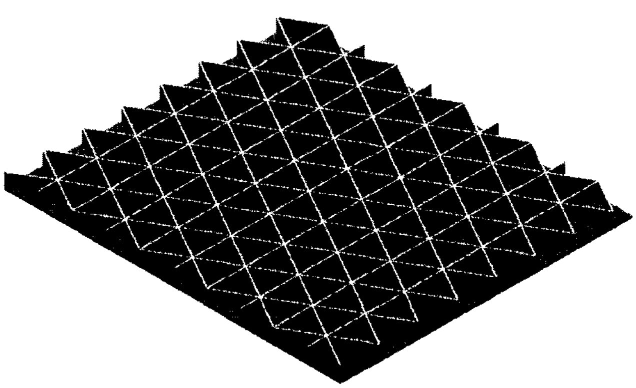


Figure 3.3—Unflanged isogrid construction

Material

PSS is constructed using lightweight GFRP material. In order in meet the severe launch environments, high strength and high modulus PAN-based carbon fibers have been chosen. To meet the stringent thermal and dimensional stability requirements, M55J prepreg tape impregnated with polycyanate resin is the baseline choice of composite material and resin system for the PSS. During the preliminary analysis and material trades, isogrid panel structure based on quasi-isotropic lay-up of [0, ±60] or [0, ±45, 90] would yield the lowest predicted CTE. Past experience and tests have shown that the CTE based on quasi-isotropic lay-up using M55J is in the 0.1 to 0.2 ppm/°C.

The selection of polycyanate resin system over epoxies is due to low moisture absorption and low out-gassing properties. The improved moisture absorption and out-gassing properties will greatly enhance the PSS performance. Since the distortions due to moisture are controlled by the fiber stiffness to control resin expansion due to moisture absorption, a polycyanate resin system with lower moisture absorption will have lower dimensional change due to dry-out on-orbit. Other benefit of polycyanate resins is their low out-gassing characteristics

Additionally polycyanates have been shown to be more resistant to microcracking under thermal cycling over the traditional epoxies. (Microcracking occurs due to mismatch in the CTE between matrix resins and carbon fibers that may result in significant internal stress at low temperatures. Microcracks are formed when internal stress equals the tensile strength of the resin. Microcracking is not desirable as it can weaken a composite and also result in dimensional changes from expansion and contraction.)

Table 3.1. Polycyanate and Epoxy Properties

	Typical Values (175°C Cure)		
Neat Resin Properties	**Polycyanates**	**Epoxies**	**Design Parameters**
Moisture absorption (%)	0.6 to 2.5	4 to 7	Moisture stability and contamination
Out-gassing, TML (%)	0.1 to 0.3	0.3 to 1.5	Contamination
Coefficient of thermal expansion, CTE (ppm/°C)	40	60	Dimensional stability

Table 3.2. M55J/Polycyanate Properties

	Design Values	
M55J Properties	**Lamina**	**Quasi-isotropic Laminate**
Young's Modulus, E_1 (10^9 x Pa)	300	106
Young's Modulus, E_2 (10^9 x Pa)	6.9	106
Shear Modulus, G_{12} (10^9 x Pa)	4.6	40
Poison Ratio	0.3	0.3
CTE, α_1 (ppm/°C)	-0.88	-0.01
CTE, α_2 (ppm/°C)	29.4	-0.01

- M55J is high strength and modulus PAN-based carbon fibers. M55J/RS-3C pre-impregnated with a polycyanate resin system has been used extensively in many space structures.
- PSS isogrid structure is fabricated using well-characterized M55J material. The primary design feature used to minimize thermal distortions is to use low CTE graphite/polycyanate laminates. The CTE properties for quasi-isotropic lay-up M55J laminates are in 0.1 to 0.2 ppm/°C.

Detailed Structural and Material Design Considerations.

The challenge in employing composite laminates for dimensionally stable applications is to control various sources of dimensional instability through material selection, design approaches and manufacturing techniques.

Structure stability control via design involves the implementation of sound design practices such as:

1. Elimination of trans-thickness CTE effects of the CFRP laminate whenever possible
2. Maintain material and geometric symmetry wherever possible. (i.e. balance, symmetric laminates/sandwich constructions, bond joints, material splices, and egg-crating configurations).
3. Maintain control of adhesive bond line thickness.
4. Avoid the use of angle clips, bend radii with small radius-to-thickness ratios (for thermal considerations)
5. Minimize CTE differences between adjacent materials
6. Structurally isolate unavoidable thermal deflections from sensitive parts in the direction of critical deflections.

Composites:

The critical stability requirements of the PSS drive the material selection to a thermally inert material such as composites. The structural stiffness required for the PSS call for the use of a high stiffness-to-weight ratio material. A high modulus graphite fiber system such as M55J pitch fiber is a good candidate material for the structure. When used in a pseudo-isotropic lay-up stacking sequence, this material has a CTE of -0.1 PPM/°F over the temperature requirements for the structure. This fiber also yields an effective modulus of elasticity of 14.5 msi also for a pseudo-isotropic laminate. This fiber system is available in thin prepregs (typically 0.0025 inch) that is preferred for stable structure applications.

In conjunction with the M55 fiber, a cyanate ester resin system would be a good selection for the prepreg resin component. Cyanate ester resins have a good resistance to microcracking as found is previous structure designs and has high design allowables for matrix-dominated properties such as bond joint strengths, compression and shear strengths. This material meets NASA out-gassing requirements for volatiles. The prepreg can be fabricated as a net resin system eliminating the need for prebleeding or dubulking operations in laminate fabrication. There is a significant history of use in previous critical dimensionally stable structures.

Metals:

The preferred design practice is to provide metallic interfaces for all components to allow accuracy and repeatability but as a result of their larger CTE values than composites, the metal interfaces contribute to thermal instability in the design. For best compatibility with CFRP structures, Invar has the best CTE match but weight is the drawback. Titanium is an acceptable alternate fitting material where the structure temperature range is narrow enough to not contribute to thermal strain due to CTE mismatch.

Adhesives:

Strength, stability (resistance to creep), and thermal (CTE) mismatch are considerations in the selection of an adhesive. The preferred design practice is to employ only room temperature curing adhesives in assembly of instrument structures. A good candidate adhesive for the PSS is Hysol's EA9394. this adhesive features high strength and toughness, resistance to creep, a long pot life, ease of use due to thixotropicity, and satisfies all out-gassing requirements. Hysol's EA9394 has been used extensively in the fabrication of many other space flight instrument structures.

Design Approach/Methodology

Based on the unique requirements of the PSS the design approach for the structure must be determined. Two basic design methodologies can be taken for the PSS:

1. CFRP skins to honeycomb core (aluminum, graphite/epoxy)
2. CFRP skins to a discrete CFRP rib core

These two design approaches will be discussed in light of for considerations that influence optical bench design and performance.

1. Analytical considerations
2. Construction methods (core and joints)
3. Adhesive considerations
4. Hygroscopic considerations

Analytical considerations

Based upon the design approach selected the PSS must be modeled with finite element modeling used as the primary analysis tool. When the design consists of honeycomb core, sandwich elements with effective properties are normally utilized. A common oversight is the determination of reduced allowable strengths based upon core depth. Most core strengths are based upon testing of .50 to .625 inch thick honeycomb specimens. With the increase of core depth there is a corresponding decrease in strength. Most optical benches are fairly thick and the aspect ratio of the elements is suspect unless a very coarse grid is used.

An alternate approach for modeling honeycomb core designs is with the use of solid elements. The drawback is that the model sizes can quickly become very large. Effective properties for thicker core must again be determined. If plate elements are utilized to model the face sheets and solid elements are used to model the core, there is a loss in the transfer of rotational degrees of freedom between the two element types. The analyst can use solid elements to model the face skins in order to correct this. To keep the proper elements aspect ratio for benches with relatively thin face sheets, the finite element mesh gets more refined and computation costs increase dramatically.

An advantage to analyzing a discrete rib design is that each structural component can be accurately modeled without the use of effective properties. The finite element mesh can be locally refined in areas of concern. For weight critical optical benches, each rib thickness can be minimized with analysis optimization or design sensitivity analysis techniques. The thickness of individual core ribs can be changed to improve performance instead of selecting a higher density honeycomb core. If stiffness is the design driver, an effective technique to increase the modal frequency is the addition of strongbacks or beams to tie the support points together. The ribbed core is will suited for this type of optimization. Optical alignment under gravity load is often the most difficult design requirement to satisfy. For this requirement honeycomb core has little flexibility. The ribbed core design can utilize an optimization analysis to examine the contribution of each rib and skin on alignment and modify the core design to improve performance.

Some drawbacks to analyzing a discrete rib core optical bench design are:

1. The finite element model can be more labor intensive to create since each rib has a defined location. The perimeter of the bench cannot be modeled and then automatically mesh the interior structure as with a honeycomb core model.
2. Modifications to the model from design changes can be more time consuming when revising insert and fitting locations because the internal rib structure typically is globally affected as compared to the honeycomb model.

Construction Methods:

Construction of the two design types of optical benches, honeycomb core and discrete rib will be discussed with regard to core and joint configurations.

Internal Core:

The honeycomb core construction initially appears to be the simplest method to employ in bench construction. Top and bottom skins are easily bonded to honeycomb core with possibly edge close outs added for stiffness. Location of fittings are easily drilled and potted in place. Densification of the core if needed in highly loaded areas is accomplished by the local addition of patches of higher core density or applying potting compound to fill the core cells and distribute the loads.

There are some compromises to thermal stability by utilizing this core approach.

1. There is a built in orthopropic behavior in the core from the warp and fill directions of the honeycomb.
2. Transferring shear loads from the core to the edge close outs can require potting the core perimeter. The addition of potting compound that is hygrothermally unstable compromises the design with peel problems as a result.
3. Bonding honeycomb core to face skins with the use of film adhesives requires elevated cure temperatures that detract from the stability of structures due to the cure temperature gradient induced distortions.
4. Metallic honeycomb core bonded to low CTE composite face skins induces thermally dissimilar material stress.
5. Through the thickness CTE properties of honeycomb panels introduces a significant challenge to designing thermally stable structures.

The discrete core design utilizes CFRP ribs to form a grid/core structure that is bonded to the face skins. The rib spacing geometry is customized to meet the required loading conditions and fitting positional requirements. The advantages of the discrete core design are:

1. Ribs can be located only where required by design. This approach can yield the greatest stiffness to weight ratio.
2. The entire core structure can be fabricated as a subassembly with the discrete ribs egg crated together in a way to provide structural continuity over the entire dimensions of the bench.
3. The core features the identical coefficient of thermal expansion as the face skins for a more stable bench design.
4. The addition of thin gauge angle clips in localized areas increases face skin to rib core bondline strengths if required.
5. The adverse through thickness properties of the face skins can be eliminated by attaching the metallic fittings or inserts directly to the underlying rib core structure.

Some drawbacks to the discrete rib approach are:

1. If the bench design requires a significant amount of highly loaded inserts spaced closely together the discrete rib approach may be more labor intensive than honeycomb core.
2. The design approach does not provide as much flexibility for last minute changes in envelope or fitting location.

Joint Configuration

The joining of the composite details in the discrete rib bench design has a significant impact on the overall stability and strength of the structure. The discrete rib construction can position the ribs to provide for direct interface attachment. Rib thickness can also be customized to meet the required thermal, stiffness, and structural loading conditions. For the discrete rib design approach, special consideration must be given to the rib-to-skin and rib-to-rib bond joint interfaces. Three basic CFRP joint types have been used for optical benches:

1. Unclipped butt joints
2. Clipped butt joints
3. Mortise and tenon joints

The joint type is selected based on factors of stress levels in the joint, weight, and cost. The addition of angle clips can further increase the joint strength with a minimum of additional weight and the angle clips can be applied in localized areas of stress as required. Thin gauge angle clips are preferred as thick section clips do not add significant increases in strength but are susceptible to hygrothermal effects due to springback that can introduce distortion to the bench.

Mortise and tenon joints can also be employed and have an equivalent effect as a clipped joint but with no significant weight penalty. There is a noticeable cost in machining and assembly time with this joint technique if not applied only as needed to the design.

Another type of joint is for graphite rib to metal interface fittings. Typically metal interfaces are required for attachment of instruments on the optical bench. The general practice with discrete rib structure designs is to enable the fitting to transfer load directly to the underlying rib core structure. By applying this principal all high expansion through the thickness effects of the CFRP face skins are eliminated which contributes to thermal stability of the structure.

Joint construction:

Optical benches are generally fabricated using room temperature curing adhesives. This is dictated by the type of tooling utilized to obtain precision mounting interfaces on the structure. Precision jigs and fixtures are not typically subjected to elevated temperatures for curing some adhesives and would negate the precision built into the tooling. Honeycomb core if used for optical bench construction is at an inherent disadvantage because heat activated film adhesives are not suitable for precision tooling alignment during construction. Room temperature curing adhesives on honeycomb core are also less desirable for stability because of the large number of core cell surfaces that require adhesive application. Further instability problems are created if core filling potting material is used on the periphery or at interface fitting locations. Potting adhesives increase weight and in them selves are a source of high CTE mismatch to the CFRP components.

Graphite discrete rib core designs are very suitable to room temperature adhesives from a weight and stability aspect. During bonding of discrete ribs the adhesive is only applied to the interface of the rib top to skin allowing for a minimum usage of adhesive.

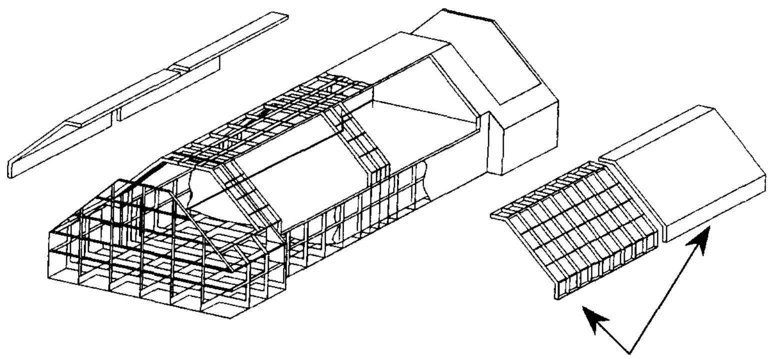


Figure 3.4 Structural design details of PSS

4. VIBRATION ISOLATION

Vibration sources on the SIM Flight System include the reaction wheels, high-gain antenna motion and solar array motion. Generally, the antenna and solar array jitter can be dealt with by operationally restricting motion to not occur during science collection times. However, the reaction wheels must remain operational all during science data collection, so the vibration caused by minute imbalances in the wheels must be prevented from passing to the optics, especially to the astrometric beam combiners. Since the reaction wheels reside in the backpack, this is accomplished via a two-stage passive isolation system.

Figure 4.1 below shows the frequency spectrum of allowable motion of the PSS resulting from vibration. The frequency curves reflect active optics attenuation for fringe tracking with a 100 Hz bandwidth, and the 10-msec capture time for acquisition. At low frequency, the cutoff is a function of the 3.5 mm maximum stroke of the delay line. High frequency allowable motion is a function of the astrometric beam combiner's ability to maintain fringe-tracking lock and of the ABC's ability to capture fringes in acquisition mode in the presence of vibration. Note that the acquisition mode and the fringe-tracking mode are mutually exclusive mode of the SIM instrument. Thus at any given frequency, the allowable motion is the lower of the two limits.

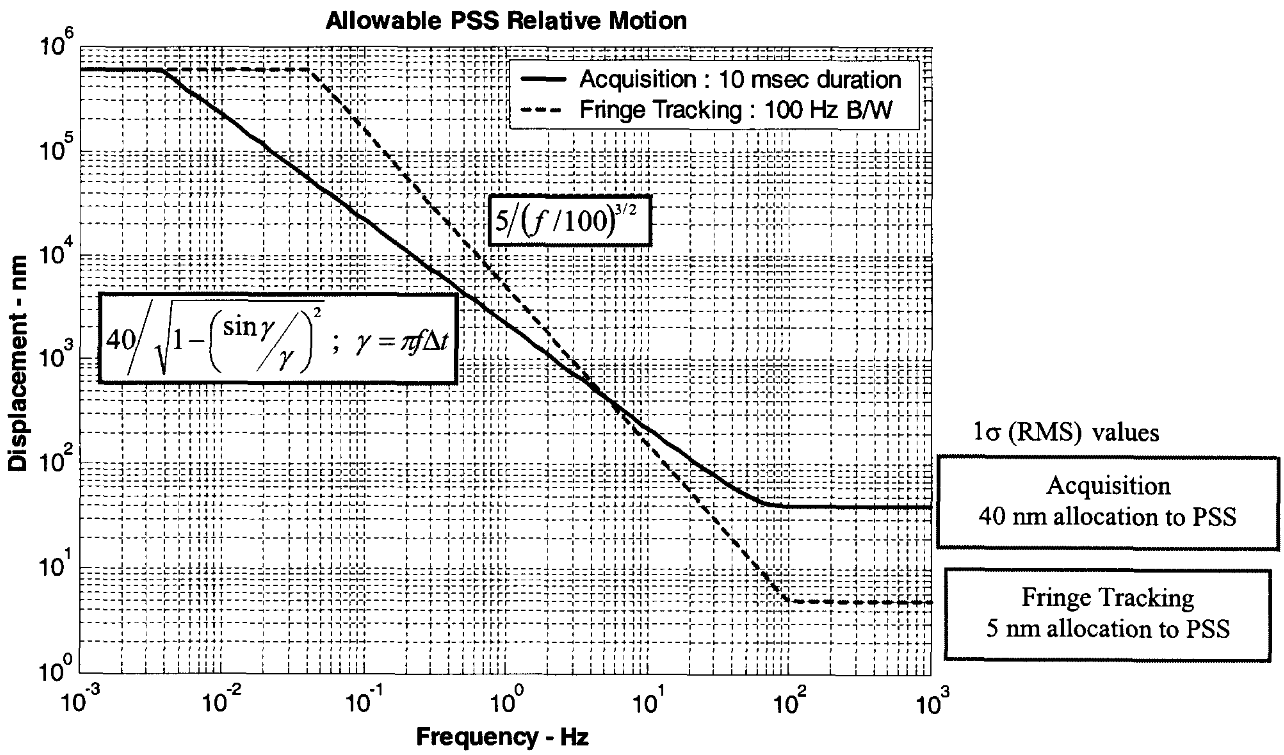


Figure 4.1—Allowable PSS relative motion at optics mounts

Isolation of vibration sources from the PSS and from the optics is accomplished primarily within the backpack, since that is the source of most of the vibration. Vibration isolation is accomplished in two steps: isolation of the reaction wheel jitter from the backpack structure and isolation of the backpack structure from the PSS.

4.1 Reaction Wheel Jitter Isolation.

The SIM Flight System employs the same reaction wheel that was used for Chandra, the RDR-68 reaction wheel from Teldix GmbH. Momentum management studies performed on the Classic configuration showed that these wheels would be adequate for SIM. This study will need to be revisited with the current configuration, since mass properties are quite different, however to first order it is expected that the baseline solution will be satisfactory.

Given the similarities between SIM and Chandra, the issue of reaction wheel jitter isolation was first addressed by employing the reaction wheel isolators developed on Chandra. This isolator is shown in Figure 4.2. The Chandra reaction wheel isolator assembly (RWIA) provides an aluminum cradle to house the wheel assembly isolated from a triangular base by six spring assemblies consisting of a parallel combination a metallic spring and visco-elastomeric material used as a damper. The RWIA provides 5 degrees of freedom of vibration isolation in the range of 7 to 13 Hz (no isolation about the RWA spin axis) that is designed to damp the fundamental modes of the wheel in its normal operating range.

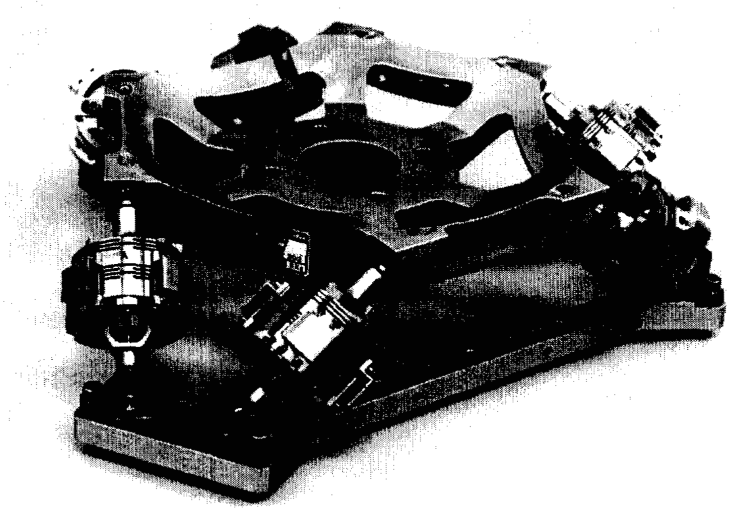


Figure 4.2—Chandra reaction wheel isolator assembly

The line drawing below shows a Teldix wheel mounted on the RWIA, and also shows the signal and power cable routing from the isolator mount (spacecraft side) to the wheel. Careful attention must be paid to this cable routing to avoid "shorting out" the isolator with the relatively stiff cable.

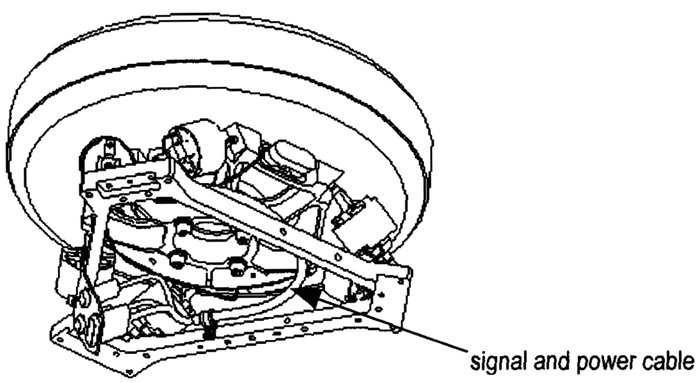


Figure 4.3—Line drawing of Teldix RDR-68 reaction wheel mounted on RWIA

4.2 Backpack isolation.

The vibration isolation provided by the Chandra RWIA is not adequate to achieve the isolation levels demanded of Figure 4.1. In addition, other potential vibration sources exist in the backpack that must also be isolated from the PSS. Therefore a second stage of isolation will be provided between the backpack structure and the PSS.

Initial studies of this isolation system proposed isolators of the type used in the Chandra RWIA, sized appropriately and tuned to the appropriate frequency for the much larger backpack assembly. In the process of developing an isolation system for the SIM Test Bed-3 (STB-3), however, a more economical isolation system was developed that proved adequate to isolate backpack jitter from the PSS. See Bronowicki, et al[4], for details.

The isolators developed for STB-3 are shown in Figure 4.4. They consist of titanium flexures that mount to the PSS (at the left end of the tubes) and aluminum fittings that attach to the backpack structure (at the right end). Between the end fittings are fiberglass tubes wrapped with visco-elastic material and over-wrapped with a segmented graphite tube.

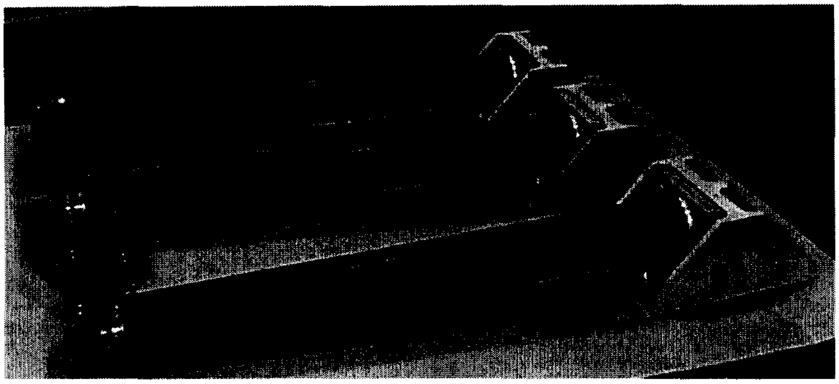


Figure 4.4—Backpack isolators developed for STB-3

Figure 4.5 shows the isolators mounted in the backpack with the top panel removed. The titanium flexures will protrude through the top panel and attach to the PSS. During launch the backpack and PSS will be rigidly connected via launch locks. Once on orbit the launch locks are released allowing the backpack to pop down away from the PSS. Enough headroom must be allowed between the backpack and the PSS so that testing in a 1-g environment will be possible.

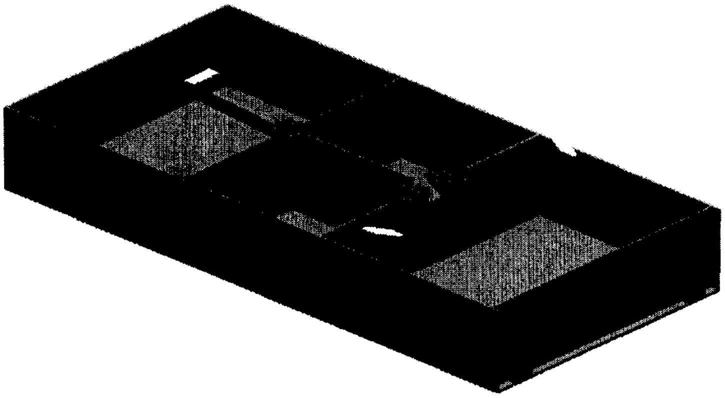


Figure 4.5—Backpack isolators mounted in backpack

Figure 4.6 shows analytically how this isolation system will perform in damping reaction wheel jitter from the optics. The acquisition and tracking filters shown in Figure 4.1 have been applied to this data, so the requirements appear flat.

In this analysis, three Teldix reaction wheels are used, the results squared, summed and multiplied by 2/3 to reflect 2 of the wheels on a peak. The result is then square rooted. The plots show plenty of margin in both the fringe tracking mode and acquisition mode. It should be noted that these are early results, so the more margin the better at this point. Other design options are available should this margin degrade significantly, such as damping the structure itself, both in the backpack and the PSS.

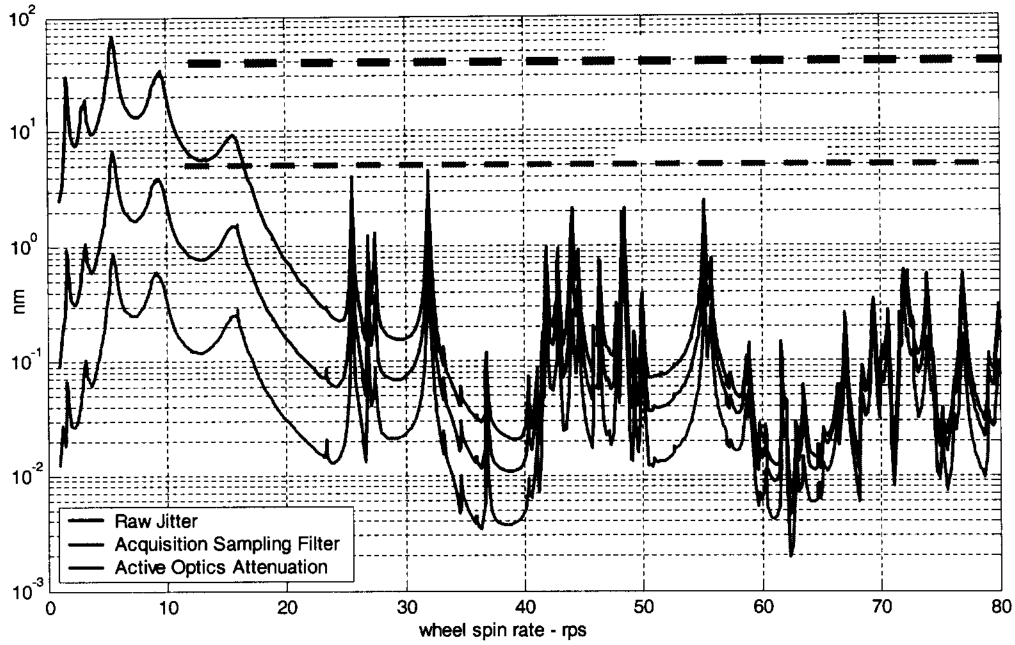


Figure 4.6—Reaction wheel jitter effects on optical path difference

5. THERMAL CONTROL

Thermal control of the PSS has two objectives. First, we must control the temperature of the PSS structure such that CTE effects are less than the position stability requirements. Second, we must provide a thermally stable environment within the PSS so that temperature stabilities of the optics in the milli-Kelvin range can be achieved.

The majority of the thermal design and analysis that has been done for SIM was performed on the Classic configuration. In that configuration, several thermal design challenges existed that are no longer applicable, namely the thermal characteristics of the metallic hinges and mechanisms for the deployable structure, and the 9-meter long metrology boom, with temperature stability requirements nearly as severe as the PSS itself. The PSS design that resulted from the reconfiguration of 2001, however, retained enough similarities to the Classic PSS design that, at least to first order, design decisions made then are applicable today. A detailed thermal distortion analysis will be performed later this year to confirm that assertion.

The salient features of the PSS thermal control design are illustrated in Figure 5.1. The basic approach is a cold biased system with positive heater control at a temperature level above the equilibrium environmental temperature. That necessitates two features: A multi-layer insulation (MLI) with very low effective emissivity (ϵ^*) and an outer layer solar absorptance/emittance ratio that enables the EOL insulation temperature at maximum solar load to remain below the PSS control level.

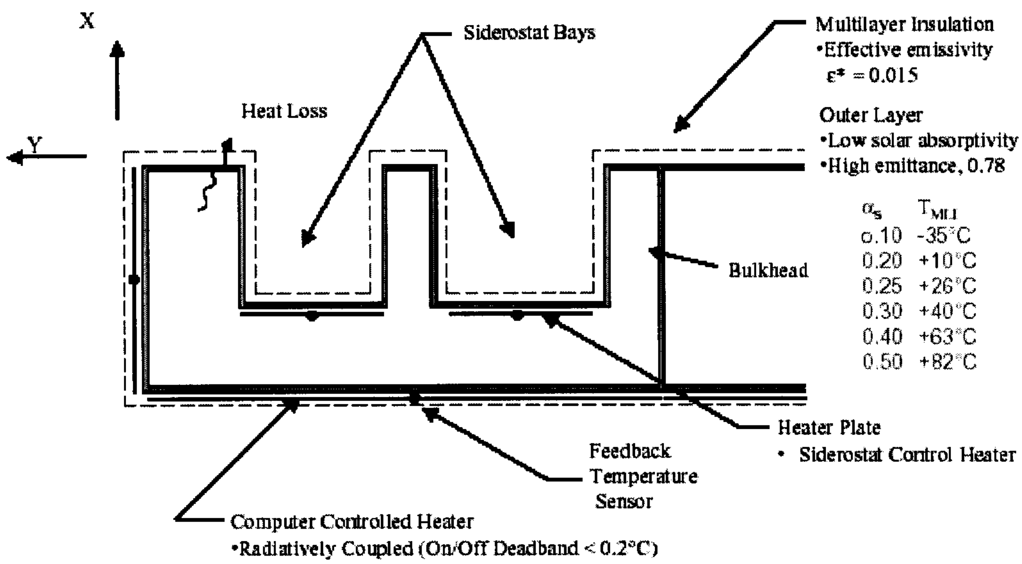


Figure 5.1—Basic PSS thermal control approach

The MLI design was borrowed directly from the approach used for the Chandra X-ray Observatory. The design, shown in Figure 5.2, consists of 22 layers of aluminized Kapton separated by Dacron scrim separators. The outer layers of silvered Teflon and Kapton provide a durable outer surface as well as the necessary solar absorptance and emittance properties.

The heater design represents the principal challenge for PSS thermal control. To achieve the required measure of temperature stability, two approaches were considered. The first was attaching heaters directly to the PSS structure. Chandra used this approach to control the temperature of the optical bench assembly, the major structural element of the telescope. However, SIM's temperature control requirements are approximately five times as stringent as Chandra's. To achieve our temperature control goals with this approach would require a more exotic and expensive design, such as high-conductivity fibers in the graphite facesheets to avoid hot spots. The selected methodology is to couple the heat radiatively to the structure by mounting the heaters on thin (3- to 6-mm) graphite panels that are separated from the PSS structure by graphite or fiberglass standoffs (see Figure 5.3). This provides a constant-temperature radiant enclosure for the PSS structure and the optics.

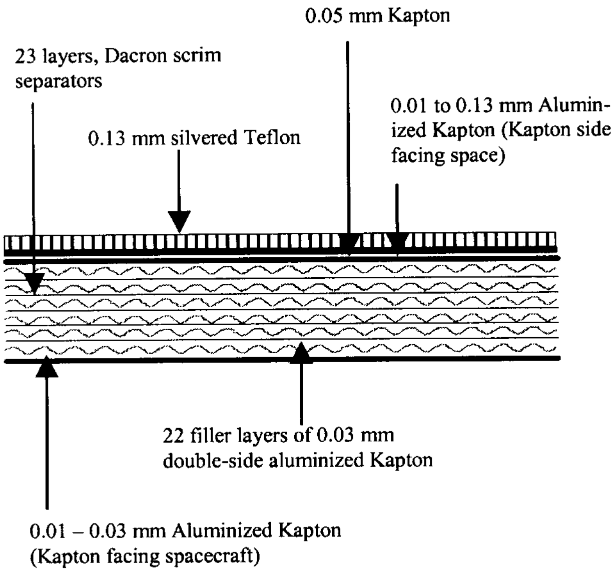


Figure 5.2—High-performance multi-layer insulation

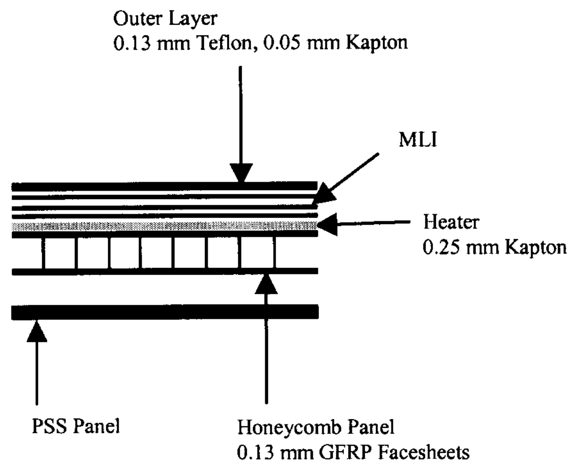


Figure 5.3—Thermal stability control using thermal blanket and radiative control heater.

Thermal control of the structure to the levels required is achieved by controlling the heaters to a setpoint in the spacecraft computer to a deadband of ±0.2°C. The heater setpoint is always maintained above the external MLI temperature. As shown in Figure 5.1, as solar absorptance goes up, so will the external MLI temperature. For most of the mission life, when α_S is less than or equal to 0.20, the setpoint will nominally be at 20°C. As α_S increases beyond 0.20 with age, the setpoint will be increased to maintain a positive heat flow out of the system.

Another key feature to maintaining temperature stability is that the system time constants are designed such that response is slow compared to the heater on/off frequency. Because the heaters are radiatively coupled to the structure rather than conductively, the structure responds to the time-averaged environmental temperatures, not the high-frequency heater cycles.

When analyzing the thermal performance of this system, all sources of thermal gradients have to be considered and addressed, if not in the preliminary analysis that we have been engaged in so far, then certainly in the detailed analysis we will do later in the program. Sources of temperature gradients arise from the environment, such as variations in solar heating, variation in the eccentricity of the orbit, variability is insulation effectiveness, variation in external optical properties, and variation in solar array shading and IR backloading. Also contributing to temperature gradients are the details of the heater system design. The location of feedback sensors (thermistors) within a heater zone, the number of heater zones (and size of the heater plates) and the drift in temperature sensors can all cause temperature gradients. Other heat sources inside the PSS can affect temperature gradients, such as electronic units that must be mounted close to cameras and other optical elements, and even heating caused by the harnesses within the PSS. Finally, penetrations of the radiant enclosure by such elements as attach points to the backpack must be dealt with in the detailed design of the PSS thermal system.

As was mentioned earlier, an analysis of the thermal control performance of this design was performed for the SIM Classic design. The most demanding mission scenario that was addressed in this analysis was the case of a 120-degree rotation about the Y-axis in steps of 7.5 degrees each hour. Heater setpoints were at 20±0.2°C and solar absorptance at 0.20 for this case. Steady-state temperatures on the sunlit exterior of the MLI reached close to the heater control temperature, due to the assumed condition of the MLI. However, both interior temperatures and PSS structural temperatures were well within bounds. Figure 5.4 below shows a PSS panel temperature response to this scenario. The panel temperature stays well within 0.1°C of the 20°C setpoint. In this case internal temperatures were within 0.05°C of the set-point.

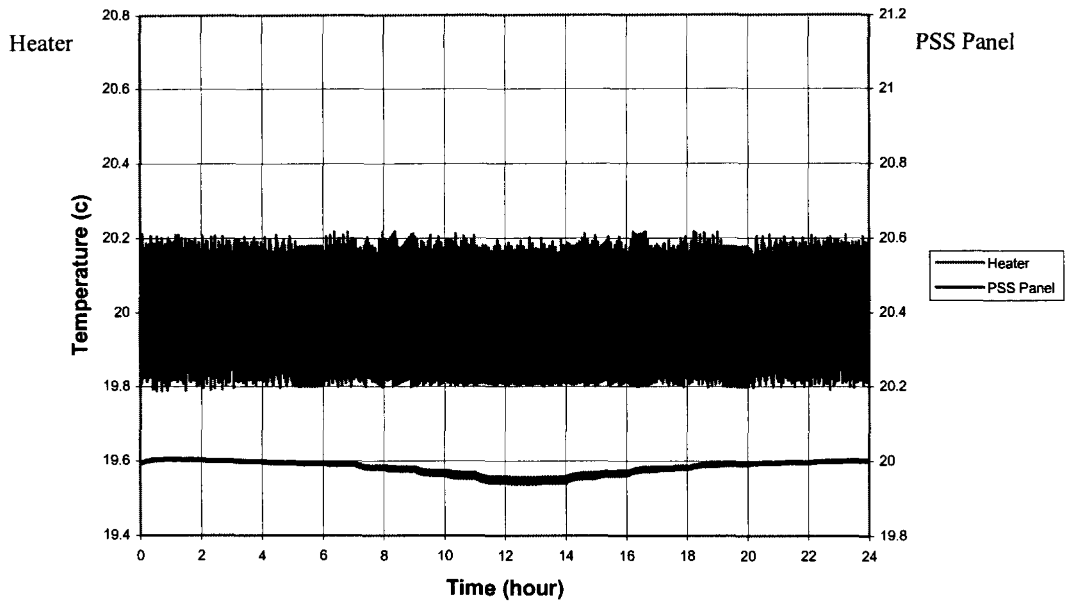


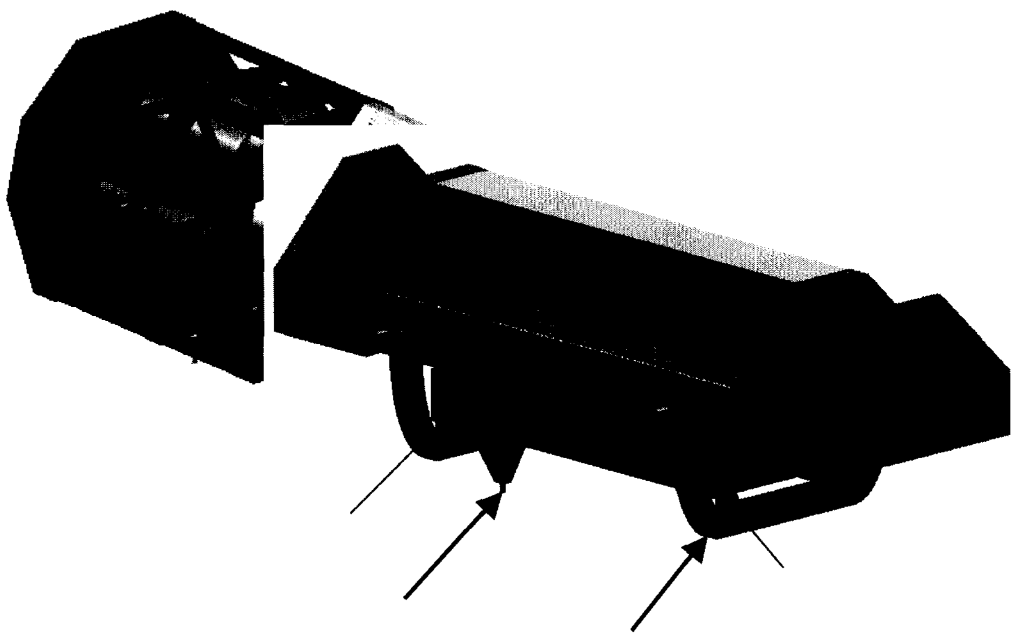
Figure 5.4—PSS structural panel response to worst-case mission scenario.

While analytically it appears that the thermal control challenges of SIM can be met with relative ease, the implementation of this design will be another matter. The closed-loop heater system described herein is far from straightforward, and will require careful attention in both analysis and design.

Further discussion of PSS thermal control is contained in Aaron, et al.[5]

6. INFLUENCE OF LAUNCH ENVIRONMENT

When developing the conceptual design for the PSS structure and other parts of the SIM Flight System, every attempt was made to minimize the deleterious impacts of the Shuttle on the PSS design. As much as possible our goal was to allow the design effort to focus more on the PSS as a home for the interferometer optics and less on its being a structural component of the Shuttle launch vehicle. However, it must be said that in a number ways the fact that the Space Shuttle is the baseline launch vehicle makes the job easier, not more challenging. Figure 6.1 shows a conceptual view of the SIM Flight System and Integral Propulsion Module in the Shuttle bay.



fitting

Figure 6.1—SIM and the Integral Propulsion Module in Shuttle bay

The principal ways that the Shuttle influences the PSS design are as follows:

Monolithic vs. deployable structure. The length of the Shuttle bay made it possible for SIM to consider a monolithic structure design rather than the deployable structure of SIM Classic. This simplified the design of the PSS dramatically and eliminated a major concern in the deployable design: microdynamics effects due to the latches that held the two halves of the structure together after deployment on orbit.

Weight concerns. Due to the size of SIM and the 15,000 kg of fuel that the IPM must carry, weight is a major concern in the SIM design. For this reason, walls of the PSS are made as thin as possible but still strong enough to support the optics and provide on-orbit stiffness as well as strength during launch. The truss structure seen in section 3 is one result of that concern. In addition, the "roof" of the PSS will be constructed of as thin a panel structure as possible, since it does not have any direct bearing on the structural stability of the optics mounts.

Support of the PSS in the Shuttle bay. One of the major constraints in a Shuttle launch is the manner in which the payload interacts structurally and dynamically with the Shuttle structure during launch. Limits exist on loads that can be applied to the attach points to the Shuttle (the longerons) and on structural stiffness of the payload and its dynamic interaction with the Shuttle and its flight control system.

Our desire to limit the launch loads on the PSS first led to decoupling the PSS from the Shuttle entirely in a primary load path sense. The PSS is launch-locked to the backpack. It is the backpack that is attached to the Shuttle longerons via the cradles and to the IPM via a launch adapter. The result was the aforementioned narrowing of the PSS structure so the cradles could reach the Shuttle payload bay attach fittings. An additional benefit of this concept is that the large stainless steel fittings necessary to attach a payload to the Shuttle will not penetrate the controlled thermal environment of the PSS where CTE mismatch effects would wreak havoc on our structural stability requirements.

Initial finite element model (FEM) studies of the IPM/SIM payload with SIM hard mounted to the IPM and a single forward cradle showed a combined natural frequency of 4.5 Hz. While less than the desired 5.1 Hz, conversations with individuals from Boeing indicated that this was acceptable. However, the launch loads on the Shuttle longerons were high (90 kips) as were the loads on the IPM-SIM interface (800,000 in-lb moment). Dealing with those loads was adding weight to the SIM and IPM design that we could not afford.

The current approach to mounting SIM in the Shuttle bay is to effectively have two almost separate payloads within the bay. The IPM and the SIM Flight System are in effect separately mounted with 5-point attachment schemes. Because the IPM maximum thrust produces acceleration of less than 0.03 g's, the connection from the IPM to SIM can be relatively soft, thus reducing moments between the IPM and SIM and interface loads at the longerons.

7. SUMMARY

This paper has presented the conceptual design of the precision structure for the Space Interferometry Mission. The three major elements of the design of the PSS have been addressed: structural stability, vibration isolation and thermal control. Within the analytical environment that this design has been developed, we meet all our requirements. As we proceed toward a PDR in May 2005, these analyses will be refined and a structural test article of the PSS will be developed to address many of the implementation issues involved in this design, some of which have been addressed here.

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