Space Interferometry Mission: Flight System & Configuration Overview

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ABSTRACT

In 2009, NASA's Origins Program will launch the Space Interferometry Mission (SIM), a 10-meter-baseline optical interferometry instrument, into an Earth-trailing solar orbit. This instrument will be comprised of four parallel optical interferometers whose prime mission objective is to perform astrometric measurements at unprecedented accuracy. Launched by the Space Shuttle and boosted into its final trajectory by an integral propulsion system, SIM will collect data for more than five years in the search for extra-solar system planets.

NASA has assembled an integrated Jet Propulsion Laboratory (JPL)/Industry team comprised of TRW, Lockheed Martin, and Caltech to formulate a reference design to meet the SIM science objectives. Addressing unique technical challenges has proven to be a formidable task in numerous aspects of the system definition, from component development to system-level integration and test. Parallel activities to develop and test the necessary enabling technologies for SIM are coupled with the ongoing flight system design.

The flight system design poses unique challenges in many areas, including geometric aspects of the layout, stability of the precision structure, thermal control, active vibration suppression, picometer-level laser metrology, etc. System-level trade studies that balance the requirements of the optics and metrology layouts and develop clean interfaces are presented herein. This paper also addresses the issues of the System Engineering processes and validation of performance specifications. Finally, this paper describes the current status of the SIM Reference System design.

1. INTRODUCTION

The Space Interferometry Mission (SIM) is a unique mission in NASA's Origins Program. Scheduled for launch in 2009, SIM will be placed in an Earth-trailing solar orbit. After an initial 6-month on-orbit calibration and checkout period, the instrument will begin a five-year science mission to obtain detailed and highly accurate astrometric measurements of stellar objects and images of stellar debris disks. This mission will make measurements with far greater accuracy than is possible from ground-based observations.

The SIM design uses three parallel interferometers mounted in a 10-meter-long structure (see Figure 1). Each interferometer collects light from paired telescopes and combines them to form fringes. Two of the three interferometers will acquire fringes on bright guide stars to make highly precise measurements of the spacecraft attitude. The third interferometer will observe the science targets and measure the target positions with respect to an astrometric grid of many thousands of stars evenly distributed around the celestial sphere.

SIM will use interferometry to measure the angles between pairs of stars to the unprecedented accuracy of about 1 μ arc second (μas). Analysis of these measurements will enable several scientific objectives to be realized. A key objective is to infer the orbital parameters of planets around nearby stars based on each star's reflex motion. SIM should be able to detect planets as small as the Earth in favorable orbits and will easily detect Saturn-mass planets. These measurements will complement radial velocity measurements already made using Earth-based telescopes, but will extend to smaller masses in longer orbits and will resolve the inclination of the orbits, something that cannot be done using the radial velocity technique. Besides planet-detection, SIM will investigate many other celestial phenomena [1].

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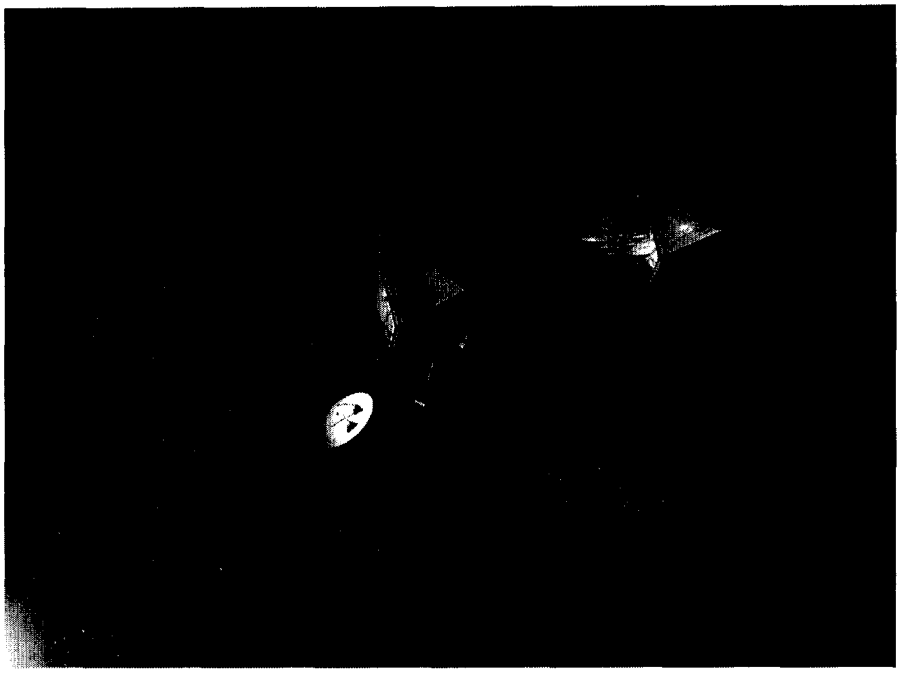

Fig 1: SIM Artist Concept.

Because some of the science objects will be quite dim (18 to 20 visual magnitude), the attitude information from the two guide interferometers locked on "brighter" guide stars will be used to point the third (science) interferometer and acquire fringes. Using this "feedforward" technique in the absence of atmospheric disturbances, SIM will achieve its desired accuracy in position measurements for a single observational period. Three primary observational modes have been defined to support Narrow Angle, Wide Angle, and reference grid closure astrometric objectives. The Narrow Angle measurements require certain levels of system stabilities over 5-minute periods. The Wide Angle astrometric observations are less stringent, requiring system-level stabilities for periods of up to one hour. The Grid work requires system stabilities and continuous measurements for periods of from many hours to potentially one or more weeks at certain times throughout the mission.

Four major organizations are combining to develop the SIM Flight System. JPL leads the overall system development and real-time control subsystem. TRW will develop the spacecraft avionics, structures (including the precision support structure, or PSS), and mechanisms along with the integral propulsion module. TRW is also responsible for the final integration and test, called Assembly, Test and Launch operations (ATLO). Lockheed Martin will develop the instrument starlight and metrology subsystems and will perform instrument integration and test. Caltech is responsible for the science planning team and science operations center, which will process the flight system data.

2. FLIGHT SYSTEM DESIGN DESCRIPTION

2.1 Overview

The flight system consists of three simultaneously operated, optical, Michelson stellar interferometers and an external metrology truss that monitors the relative orientations of the three baselines. The system is comrised of optics, actuators, sensors, and computers for acquisition and tracking of the stellar fringe pattern, the desired science data. A precision support structure (PSS) that supports all of the instrument components is attached to a heritage-based spacecraft bus. The maximum science interferometer baseline is 10 meters. At any time, one interferometer is dedicated to taking science data while the other two act as "guide" interferometers to determine the orientation of the baseline of the science interferometer. Using "bright" stars, these guide interferometers act as a high precision star tracker for the science interferometer. A fourth interferometer is provided as a redundant "spare" interferometer.

The fundamental design of a single interferometer requires that the pointing subsystem acquire the starlight photons from each arm of the interferometer. The starlight is sent through a series of relay optics in the PSS, via coarse- and fine-stage delay lines for optical path compensation, to beam combiners. The beam combiners combine the light to form fringes on a charge coupled device (CCD) detector.

SIM performs astrometry (measurement of star locations) by using a white light Michelson interferometer with a 10-m baseline. Groups of optical elements (similar to telescopes) are located at 8.75 m and 10 m apart on opposite ends of a PSS to collect the starlight. Light from these telescope-like assemblies is combined in an astrometric beam combiner (ABC) in the middle of this large instrument. Optical delay lines (ODLs) are used to adjust the path length followed by the starlight so that the wavefronts from both arms of the interferometer arrive at the detector at precisely the same time. The path lengths within the instrument are then measured to a precision (not accuracy) of a few tens of picometers (1 pm $= 10^{-12}$m) using infrared laser metrology gauges. Based on these measurements and other laser gauge measurements of the baseline length, the angle between the target star and the baseline is determined. To determine the orientation of the astrometric baseline, two other similar astrometric interferometers are used. The baselines for all the interferometers are kept as parallel as possible. The external laser metrology system measures the small amount of deviation from parallelism to make corrections to the results.

Use of two baselines enables demonstration of a technique called synthesis aperture imaging and also provides for astrometric baseline redundancy. It is critical that the three interferometer baselines are co-parallel. This is due to the fact that the two guide interferometers provide attitude information in two of the three angular directions. The third dimension is the roll about the baseline vector. Sensing of this direction is significantly relaxed if the interferometer baselines are parallel to one another.

The metrology subsystem measures distances in the interferometer critical to the high-precision angular measurements. The metrology subsystem utilizes heterodyne metrology laser gauges to measure the interferometer baseline length and the internal optical path lengths. The science requirements translate directly to a requirement on the accuracy of the metrology gauges. The metrology gauges will have to measure relative changes in internal path length with an accuracy of approximately 20 picometers.

The metrology subsystem is subdivided into the metrology fiducials, the beam launchers, and the metrology sources. The fiducials serve as the endpoints of the measurement system. The beam launchers inject laser light to measure the distance between the fiducials. Finally, the metrology source generates the optical signal and frequency offsets necessary to derive the metrology phase differences.

The laser gauges are not absolute gauges. They do not measure the actual distances involved, but rather the changes in the distances with a precision of tens of picometers. The absolute lengths are basically calibrated by using measurements of stars around the sky. A gridwork of stars spanning a large part of the celestial sphere is measured and then adjust the scale factor for the instrument to "close the grid." This is somewhat analogous to a surveyor measuring angles around a full circle and verifying that the total is equal to 360° and adjusting the scale factor to make it so [2].

As a starting point, the beam launchers can also be used as absolute distance gauges with an accuracy of a few microns. Basically, slightly different heterodyne frequencies are applied to two laser sources. The two frequencies are selected to be very close together. Both laser sources are mixed and directed into the beam launchers. The relationship between the phase measurements at the two frequencies allows one to establish the common propagation distance to an accuracy of a few microns. In a sense, the two frequencies form a static-beats envelope spatially. There is an ambiguity of a few centimeters (the length of the beats envelope), which depends on the closeness of the two frequencies. This ambiguity is sufficiently large that physical measurements on the ground ahead of time will resolve the ambiguity. The result is that the absolute distance between two corner cube fiducuals can be measured with an accuracy of a few microns. Eventually, this initial estimate is unproved.

2.2 Pointing System

In SIM, the pointing subsystem consists of two bays containing four separate, co-linear baselines. Each bay holds two guide interferometer telescopes and transfer optics and two science interferometers telescopes and associated transfer optics (one active science and one spare) (see Figure 2). Each science interferometer telescope assembly includes a siderostat and a 40-centimeter flat mirror pointed 30 degrees from the optical axis of the beam compressor. The siderostat uses two-axis flexures and voice coils to move the mirror over a 7.5-degree range [3]. The pointing system has both coarse and fine actuators. The coarse actuator acquires stars over a 15-degree field of regard without reorienting the spacecraft (see Figure 3). The fine actuator provides high-precision pointing control required for high-visibility stellar fringes.

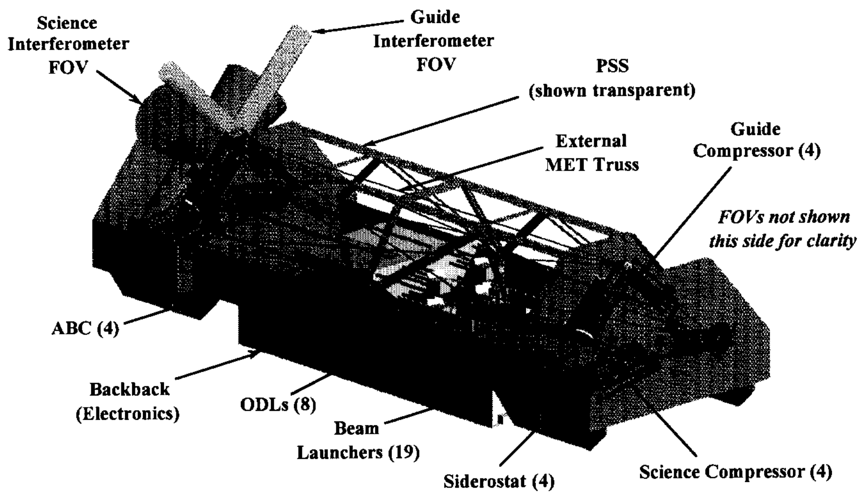

Fig. 2: Optical layout.

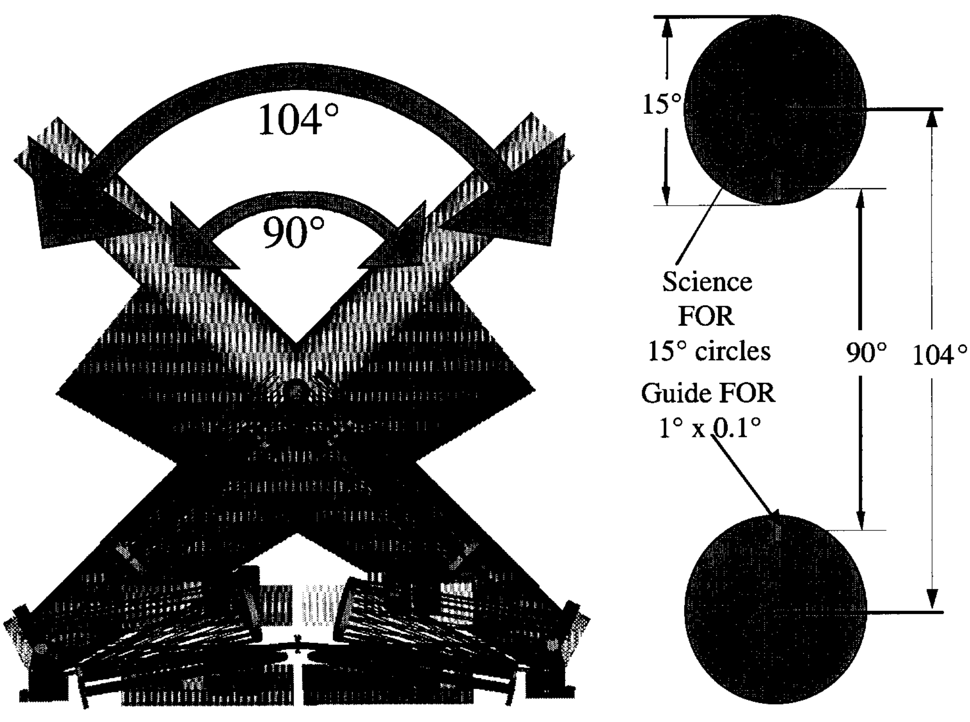

Fig. 3: End view.

The siderostat actuator has high-precision rotary encoders to provide a pointing resolution of 20 milliarcseconds. The system is also designed so that the siderostat can, in calibration mode, articulate to a position that it is facing normal to the beam compressor, thus reflecting a calibration signal back into the optical train. The beam compresses the stellar beam from a 35-centimeter collection-aperture diameter to a 5-centimeter diameter beam. This compression enables the use of smaller optics in the remainder of the optical train (for calibration between the starlight wavefront path and the path as sampled by the internal metrology system). A corner cube at the center of each siderostat mirror defines the end point of the interferometer baseline. The corner cube is physically contacted to the siderostat surface such that the vertex is coaligned with the mirror surface and the two siderostat axes. Translation actuators underneath each siderostat mirror are used to align the baselines after the initial instrument deployment to within 10 micrometers of being co-linear. The external metrology will monitor the misalignment between the baselines. Starlight exiting the beam compressor is sent to a fast steering mirror (FSM), providing the high-frequency pointing control of the starlight. The FSM is used to adjust the incoming starlight beam wavefronts to reduce the tilt in the system. From there, starlight proceeds to a turning mirror that injects the starlight into the remainder of the optical train.

In addition to the starlight collection and pointing optics, external metrology beam launchers are also mounted in the bays and form an optical "truss". Each bay houses nine beam-launcher assemblies that measure the distances between the fiducials mounted above the guide interferometers and the siderostat fiducials.

2.3 Delay Lines

From the front-end pointing system and relay optics, the starlight transfers to the optical delay lines, which modulates the pathlength difference between the two arms of any given interferometer. Like the pointing subsystem, the delay lines have multiple stage actuators. There are two optical delay lines for each interferometer. One arm of the interferometer includes the coarse stage, comprised of a band drive and stepper motor, moves the entire cat's-eye assembly by up to 2 meters, as necessary to acquire fringes for stars within a 15-degree field of regard. The other arm of the same interferometer includes the fine actuator stages, using both voice coils and Piezo-electric transducer (PZTs), provides high-bandwidth pathlength modulation to control the optical path difference precisely and reject jitter from onboard disturbance sources, such as reaction wheels or delay lines. A voice-coil stage moves the cat's-eye assembly over a 1-centimeter range at low frequencies (<10 hertz) and a PZT stage provides the high-bandwidth actuation (10 to 1,000 Hertz) with a stroke of a few micrometers. During normal observations, the delay-line coarse stage will be locked down and only the voice-coil and PZT stages will be used for pathlength control. Both those stages will be momentum compensated to minimize disturbances induced by the delay line to the rest of the instrument.

2.4 Astrometric Beam Combiner

The final element in the light path is the astrometric beam combiner, which includes the white-light fringe camera detectors, the angle-tracking detectors, the internal-metrology beam launchers, and self-calibration sources. At this point, the delay lines have compensated the pathlength difference for light from the two arms of the interferometer. A white-light fringe can form as soon as light from the two arms is combined. The fringe tracker camera in the beam combiner system records this fringe pattern. The fringe position is then used as both the science data and as a sensor signal for the delay-line actuator, allowing maximization of the signal. The beam combiner also contains a detector, called the angle tracker, to measure the tilt of the incoming wavefronts. This sensor controls the fast-steering mirror in the pointing subsystem.

The stellar fringe is spectrally dispersed using a prism to provide phase and visibility information at different wavelengths. These data are then used to extract pathlength information by the control system.

In addition to collecting the science data, the beam combiner generates the control signals for the delay lines and the pointing subsystem. For this purpose, the starlight pupil plane is divided into three regions. The inside region is used to propagate the internal metrology beam from the combiner to the optical fiducials on the siderostat mirrors. Light from the middle annulus is combined to form the stellar fringe (the science data measurement) and is sensed by the fringe tracking camera. Light from an outside annulus is used to determine the wavefront tilt and is sensed by a second camera, the angle tracking camera.

2.5 Metrology

The metrology subsystem is comprised of three primary gauging measurements: absolute metrology, external or baseline measurement, and the internal or pathlength measurement. Optical fiducials located in front of the siderostat on the science interferometers and the fiducials located above the guide interferometers define the individual interferometer baselines. The external metrology system measures the length of the interferometer baseline (and relative baseline orientation). The internal metrology measures the optical path from the beam combiner to the optical fiducial. Heterodyne metrology gauges are used to monitor the distances between the optical fiducials. A separate internal metrology gauge is used for each arm of the interferometer and is injected into the center of the starlight beam inside the beam combiner. This metrology beam will measure the path from a fiducial inside the combiner to the baseline fiducials. The internal metrology samples the center of the same optics that transmits the starlight and is referred to as sub-aperture metrology (SAM).

The external metrology truss measures the lengths and relative orientations of the three interferometer baselines. The external metrology truss contains reference fiducials interrogated by 19 metrology beam launchers that are used to triangulate on the position of each of the siderostat fiducials (see Figure 4). A 10-micron stability requirement of the starting position of the vertex position relative to the baseline for the entire 5-year mission must be maintained.

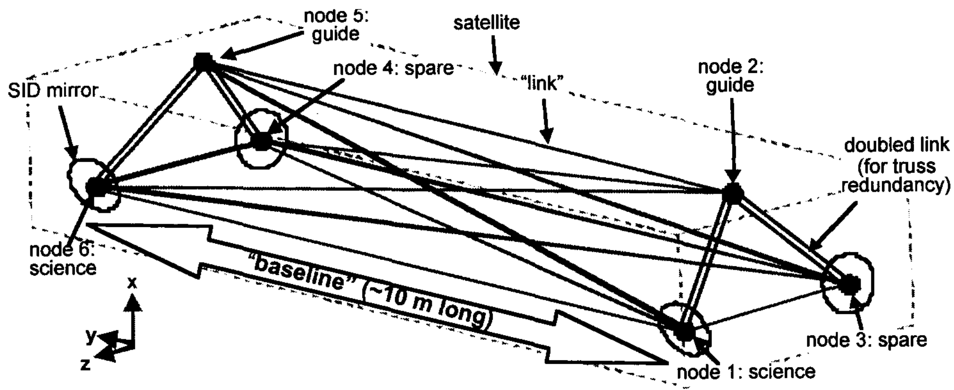

Fig. 4: External met.

The metrology subsystem uses unique double corner cubes (and in two cases, triple corner cubes) as the optical fiducials for both the external and internal metrology gauges. One face of the corner cube is used by the external metrology gauge to measure the baseline length. The other face of the same corner cube is used as a common endpoint for all four internal metrology gauges. It is critical that the vertices between the different corner cubes are co-aligned to minimize the offset between the external metrology measurement and the internal metrology measurement.

2.6 Real-Time Control

The real-time control (RTC) subsystem includes the electronics, software, and control algorithms necessary to support and run the interferometer. The SIM instrument will need to operate with limited intervention from the ground and, therefore, must perform important functions with a high level of autonomy and reliability. These functions include initial optical alignment, calibration, stellar target acquisition, angle tracking, fringe tracking, slew, and diagnostics. The real-time software will play the central role in performing these functions. The software has been architected to operate the instrument on a distributed set of multi-purpose computers.

The instrument flight software implements the set of in-flight real time command, data, and control functions required to operate the SIM flight instrument. Instrument command and data functions include startup; instrument sequence decoding and execution; storage of science and engineering data, and packetization packaging for telemetry downlink. In addition to normal instrument operations, the flight software will provide the functionality for ground testability and some level of fault protection, enabling autonomous operation without ground-assisted reconfiguration. Additionally, the instrument flight software will need to communicate with the spacecraft flight software for the routing of both uplink and downlink data. The interface is especially important, as it is the spacecraft that handles all ground-system-to-flight-system communications. The instrument data is sent to the spacecraft system to be stored on a solid-state recorder.

The SIM instrument software architecture is derived from existing ground interferometer designs as well as having some level of commonality with the StarLight interferometry mission. The software allows the use of multiple computers to control the interferometer and enables flexibility in the design of the flight instrument electronics and hardware.

The control functions enable the instrument to track on a stellar fringe and monitor the critical instrument parameters through the metrology system. The control system includes alignment, pointing control, and pathlength control. Alignment control establishes and maintains the instrument optical geometry. Alignment is typically executed after the initial instrument deployment and after a major flight system configuration change. The pointing control system includes coarse pointing and fine pointing described earlier. Coarse pointing acquisition and control actuates the siderostat motion to position and hold a target star image on the siderostat camera focal plane. Fine pointing acquisition utilizes the fast steering mirror control to position and hold the target star image location on the beam combiner focal plane. In addition, angle feed forward control algorithms are used to point the instrument on a dim science star using information from nearby bright reference stars. The pathlength control system involves control of the delay line to form a stellar fringe pattern on the beam combiner. Information from the internal and external metrology and the beam combiner are used to control the delay line in order to acquire a fringe and to keep the pathlengths through each of the interferometer arms equal. In the case of dim science targets, a pathlength feedforward control algorithm utilizes information from the guide interferometers and the attitude control system to estimate the correct position for the science delay line.

The onboard instrument electronics provide the real time processors, data busses, and component interface electronics necessary to control the SIM instrument. A total estimated processing throughput of several hundred MIPS is required on board to support command and telemetry streams concurrently with closure of the high-rate pointing, metrology, and optical pathlength difference control loops in science operational modes.

A multi-processor architecture supports partitioning of software functionality across processors and microcontrollers for flexibility in subsystem partitioning, software development, and flight system implementation, integration, and test. Data bus latency requirements are driven by the closure of three concurrent sets of phasing control loops with sampling rates in the kilohertz range and the associated estimators, pointing control, and related functions. Redundant connection to the Mil-Std-1553B spacecraft bus is provided. Single fault tolerance capability also drives the maximum allowable latencies across the instrument data bus. Fault containment regions provide a robust design in the event of unanticipated electronics problems.

2.7 Structures and Mechanisms

There are two primary structures for the Flight System, each with a different level of requirements placed on it: these are the "wing" or PSS and the "backpacks", the less precise part of the structure.

The PSS design consists of a monolithic wing structure to mechanically achieve the baseline lengths required for the science goals. Additionally, the PSS provides the containment housing to support the external metrology laser truss. The PSS also provides an active thermal control envelop for all the enclosed optics and mechanisms contained within it.

The "wing" has the two bays integrated into it along with all the relay optics, delay lines, and beam combiners. The PSS has stringent, micron-level stability and thermal requirements placed on it. This structure must maintain baseline length knowledge to the 10-micron level.

The "backpack" attaches to the base of the PSS in two sections. The first section houses the Spacecraft avionics suite and is referred to as the "spacecraft". The second "backpack" houses all the real-time control electronics that are not required to be in close proximity to their sensors or actuators. These backpacks include an isolation system to reduce dynamic disturbances and their impacts on the interferometer.

2.8 Avionics

The spacecraft provides the flight system essential operational functions, including power, attitude control, propulsion, communication, and thermal control. The primary avionics suite is based on existing components developed at TRW. Most of the avionics components will be housed in the spacecraft backpack. The command and data handling (C&DH) subsystem processor controls the spacecraft operation and thermal control and interfaces with the instrument RTC processors via the Mil-STD-1553 interface. The telecom system utilizes X-band communications. The electrical power subsystem provides uninterrupted electrical power to the spacecraft and instrument and employs a battery-clamped distribution bus providing DC power to all user loads via a solar array wing and a nickel-cadmium battery.

The attitude control subsystem (ACS) is an existing system providing 15 arc-seconds pointing accuracy per axis. The reaction wheel command and control laws are derived from the Chandra X-Ray Astronomical Facility vibration isolated wheels to provide pointing to 14 arc-seconds per axis and slew rates of 0.25 degree per second. Reaction wheel isolation will employ flight-qualified isolators. To avoid disruption of science data, solar array re-pointing and momentum unloading is performed during slew maneuvers. The propulsion subsystem is a proven off-the-shelf design used on previous NASA missions.

The thermal control subsystem is designed to meet the requirements on temperature stability and temperature gradients within the PSS and metrology boom. In the PSS, thermal stability is maintained at 20.0 +/- 0.1° C. Silvered-Teflon multi-layer Insulation ensures that sunlight illumination will not adversely impact temperature stability. Thermal control of the spacecraft incorporates conventional aluminum heat pipes so that electronics and absorbed solar heating can be transported from the sunlit side of the spacecraft to the shadowed side.

2.9 Intergral Propulsion Module

The STS or Space Shuttle is the primary Launch vehicle for the SIM flight system. The Shuttle place SIM into a low-Earth orbit (LEO). From there, a separate propulsion system developed by TRW (based on the Chandra propulsion system) has been developed to take SIM from LEO to its final Earth-trailing solar orbit. This integral propulsion module (IPM) is attached to SIM in such a way as to be decoupled from the static and dynamic loads of the SIM Flight System. It is relatively "loosely" coupled, structurally, from the PSS during launch. The IPM will be fired at the peragee each Earth orbit in a sequence of burns that, combined, will raise the SIM orbit and place it on an Earth Trailing Solar Orbit (ETSO) trajectory with a C3 of approximately .4 (Figure 5).

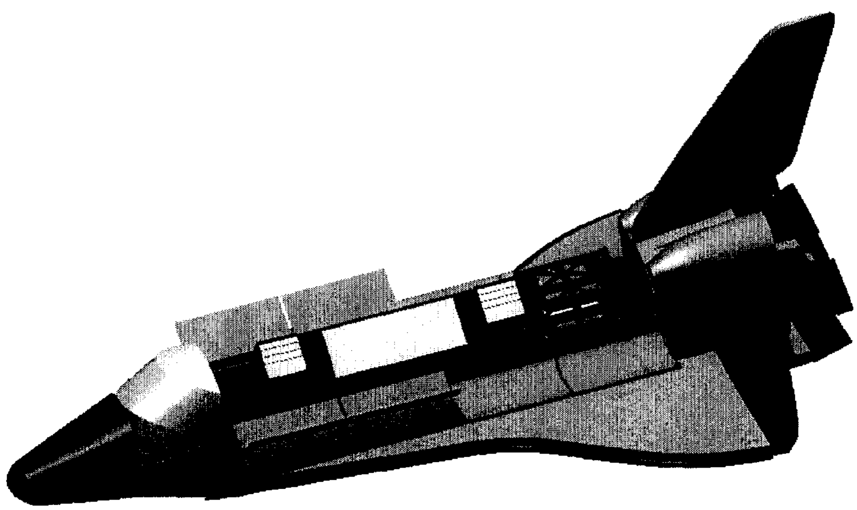

Fig. 5: SIM in Space Shuttle.

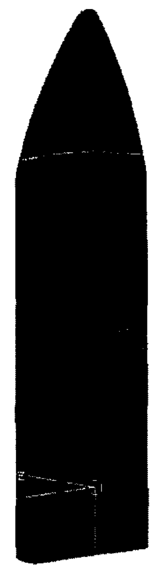

Fig. 6: SIM in EELV.

3. SYSTEM ENGINEERING PROCESS AND TRADE STUDIES

A number of technical breakthroughs are required to enable the SIM mission, challenging the system engineering task. A number of testbeds are being built to address key technology challenges of the project. The function of the system engineering and architecture task is to establish the requirements and design on the mission and instrument, translating into an engineering design the requirements and goals set forth by the project science team. A summary of the driving requirements of the instrument is shown in Table 1. System engineering also has the responsibility to provide a link between the flight mission and a concurrent technology development program, integrating the results of the technology testbeds into the flight system design. The results of this technology development program, in the form of testbeds and models, will be applied to the analysis at the system level in order to determine whether the existing technologies and detailed designs have met the requirements of the SIM project. The validation and verification matrix is a system engineering method that tracks how, where, and by what process requirements are proven. Some requirements are validated at a component or subsystem level. Other requirements demand system-level testing, while some remaining requirements can only be validated by analyses. Over the course of the instrument development cycle, system engineering will monitor the results of the technology development effort and correlate them into a validation and verification matrix. This matrix will be used in the integration and testing phase to prove that the system, as a whole, meets or exceeds its mission objectives [3].

Table 1: Requirements summary.

Instrument Requirements	
Max. Baseline Length	10 meters
# of Baselines	3 (1 guide, 2 science)
Number of Interferometers	4
Spectral Range	0.4 to 1.0 microns
# of Siderostats	8
Aperture	35 cm
Astrometric FOR	15 degrees
Instantaneous FOV	10 arcseconds
Sun Avoidance Angle	45 degrees
Est. Mass	3495 kg.
Fringe Stability	10 nm (rms)
Pointing Control	2 arcseconds
Orbital Velocity	20 mm/sec
Determination	
Spacecraft Slew Rate	15 degrees in 2 min.
Temperature Stability for	3 MilliKelvin / hour
Critical Optics	
Science Performance	
Wide Angle Astrometric	<10 microarcseconds on
Single Accuracy	18th magnitude star
Proper Motion Accuracy	3 arcseconds/yr

As is the case in the development cycle of any flight project, key reviews play a major role in examining the preparedness of the project to proceed on to the next phase and as a forcing function to achieving pre-set project schedule milestones. The system engineering team is leading the preparation for these reviews. The SIM project has significant project-level reviews coming up in the next two years. These reviews are the Preliminary Mission and System Review (PMSR), scheduled for February 2003, and the System Requirements Review (SRR), scheduled for November 2003. A third review is a combined Preliminary Design Review (PDR) and a Non-Advocate Review (NAR), scheduled for the Spring 2005. The SRR is the review that establishes the formalization of the project-level system requirements and conceptual design. The PDR/NAR is the review that is focused on a more advanced level of design and is the key "gate" the project must achieve to move beyond the formulation phase and into the implementation phases, formally known as Phases C & D of the mission.

3.1 Key Flight System Trade Studies

An important role that system engineering plays is resolving important issues that exist with the design activity. One methodology used to identify and resolve technical issues is by performing trade studies between various competing ideas or approaches. Reducing risk to the mission is always a driver when approaching resolution of system-level issues. Key flight system development and configuration trades have been used in the development of the SIM reference design. There are numerous trade studies that have been undertaken or are in process. These trade studies include:

1) A comparison of various internal beam diameters versus CC size and starlight obscurations
2) Corner cube development to handle competing internal metrology, external metrology, and testing and calibration requirements on the design
3) Choosing the number of beam launchers versus adequate redundancy
4) Telescope design option
5) Launch vehicle choice
6) Orbit selection: L2 vs. ETSO

Each of these areas involves many interacting considerations. A full description associated with each one of these could warrant a full paper each. Here, just a short overview of some of these is provided.

1) A comparison of various internal beam diameters versus CC size and Starlight obscurations:

The internal metrology beam is launched from within the astrometric beam combiner. This beam propagates out to the corner cube fiducial in front of the compressor and then returns. The round trip distance is approximately 30 m. The smaller the diameter of this beam, the greater the diffraction effects over this distance. The larger the beam, the larger the corner cube surfaces need to be to return the beam without clipping the edges. As the corner cube grows, it blocks more of the incoming star light beam, requiring the optics to grow in diameter. The corner cube size is also coupled to the geometry of the external metrology truss; therefore, this becomes a very complicated trade involving the overall configuration (in addition to the primary effects mentioned). Another related aspect is how close to the edges of the facets of the corner cube the surface quality can be maintained to permit reflection of the metrology beam with acceptably low distortion. The current nominal size of the envelope for the internal metrology beams is approximately 8 mm. This results in less than 20% area obscuration of the 35-cm diameter (uncompressed) starlight beam. That is, the resulting shadowing of the siderostat mirror by the corner cube is less than approximately 16-cm diameter. In an effort to maintain an approximately 700-mm^2 of starlight clear aperture as defined in the astrometric error budget, this implies that the siderostat must be on the order of 35 cm in diameter.

2) Corner cube development to handle competing internal metrology, external metrology, and testing and calibration requirements on the design:

   The corner cube mounted on the surface of the siderostat mirror serves several functions. Basically, the vertex of the corner cube serves as a reference point, or fiducial, for both internal metrology and external metrology as well as an optical reference point for use during calibration on the ground. To operate as a retro-reflector for beams from many different directions, the fiducial is comprised of two corner cubes with a common vertex location. The two corner cubes are collectively referred to as a double corner cube (DCC). Another fiducial in front of the guide compressors, which have no siderostat mirror, is a triple corner cube (TCC). The DCC mounted in the surface of the siderostat is angled so that it can accept all the internal and external metrology beams converging on this common reference point. This means that portions of the DCC are submerged within a hole through the Siderostat and portions protrude in front of the Siderostat. The vertex must be aligned such that it is within a few microns of (an extension of) the surface of the siderostat. Furthermore, the offset must be calibrated within a few nanometers and must remain stable over periods of a few hours to within tens of picometers. In addition, once the DCC is mounted to the Siderostat, the axes of rotation of the Siderostat gimbals axes are also aligned to the vertex within a few microns. Clearly, this is a very tricky aspect of SIM, and will require great care to accomplish successfully.

3) Choosing the number of Beam Launchers versus adequate redundancy:

   The arrangement of the beam launchers in the external metrology truss has been a significant driver of the configuration of SIM for several years. This external metrology truss has changed considerably in response to changing understanding of the constraints on SIM, as well as due to changes in the requirements levied on SIM. The truss currently has six nodes. Each node is the shared vertex of a multiple corner cube. Four nodes are formed by DCCs on the siderostat Mirrors, and two are TCCs mounted via spiders and shared by the Guide Interferometers. Metrology beams connect each node with every other node. This leads to 15 different length measurements, although a couple of these cannot be made during observation of targets, but only during calibrations with the siderostats oriented in a special way. Although there are 15 measurements, only 12 are strictly required. However, even with 15 beams, the loss of certain beams would cause a significant degradation in the overall performance of SIM. For four such beams, we have chosen to add redundant beam launchers to reduce the likelihood of loss of these particularly sensitive measurements. This is a tradeoff among cost, performance, and reliability. We have chosen to add a little more redundancy than officially required by the single point failure tolerance project policy, recognizing that the cost will be increased a small amount over the barest minimum required. This incremental cost is outweighed by the improved reliability because we incur just the recurring cost associated with extra copies of beam launchers, whereas the chance of failure is reduced significantly due to the increased redundancy.

4) Telescope design:

   In some previous versions of SIM, all the interferometers used siderostat mirrors to aim the line of sight. In order to reduce cost, we investigated options that eliminate the fairly expensive siderostats and associated gimbals and controls from the guide interferometers, but maintained them for the science interferometers. This approach led to the current configuration. The current design uses the small fast steering mirror downstream (optically) from the compressor to aim the line of sight of each guide interferometer. This approach requires a wide-angle field of view for the compressor since it remains fixed when the line of sight is steered on the sky to acquire guide stars. A three-mirror anastigmat (TMA) off-axis compressor was designed to provide the wide-angle FOV need by the fixed guides. The Science interferometers, with their siderostat mirrors, can operate with a much smaller FOV compressor. Such a compressor would probably be somewhat less expensive to develop than the TMA. However, given that a TMA was going to be developed, it turned out to be less expensive to duplicate the TMA and use it for the science interferometers rather than incur additional non-recurring engineer costs to develop a simpler compressor (in addition to the TMA). Therefore, all eight compressors use the same TMA telescope design.

5) Launch vehicle choice:

As the design of SIM has evolved, so has the choice of launch vehicle. In the past, SIM PSS was hinged so it could fit into small (relatively inexpensive) launch vehicles. The PSS has some very stringent stability requirements and the presence of hinges was a risk. Both microdynamics and thermal control of the hinge were perceived to be difficult and expensive to deal with. The launch vehicle that is assumed for the current reference design is the shuttle transport system (STS) (a.k.a., the Space Shuttle). The payload bay of the shuttle is sufficiently long that the PSS does not need to be hinged. The large volume available also eased many other aspects of the design. Given that a shuttle fleet is in operation for other purposes, the incremental cost of an additional shuttle launch is not all that much more expensive than the launch of an expendable launch vehicle having a much smaller volume and mass capability. The reduced challenge in fitting inside the available volume reduces the cost in many areas across the flight system, offsetting the increased launch vehicle cost associated with using the Shuttle. Furthermore, the Shuttle has demonstrated very reliable operations. Another option is to use an evolved expendable launch vehicle (EELV) currently being developed. Although a new launch vehicle cannot be expected to demonstrate the reliability of the shuttle, the EELVs are being developed as extensions of existing highly reliable expendable launch vehicles. The heavy-lift versions of the EELVs have payload fairing options with sufficient volume to house SIM with its monolithic (non-hinged) PSS. Furthermore, the mass that the EELV can place into SIM's orbit is significantly greater than can be achieved using the Shuttle. If the design of SIM can be simplified by using a heavy lift launch vehicle, the advantages of this option may outweigh those of the shuttle option.

As has been made evident by the trade studies listed above, complex engineering issues often traded against each other as well as against cost, risk and schedule. As the process of development matures and the SIM reference design evolves into it's preliminary and final stages during the Implementation Phase of the Project, most of these trade studies will have been addressed and documented. As the project matures, the trade studies, at the system level are greatly reduced in number as fabrication and integration approach. Changes become solidified and the system is controlled to maintain track of all changes and to limit them and their impacts on cost and schedule risk.

4. CONCLUSION

This paper has described the detailed SIM reference design and a number of key trades studies that are were factored into the reference design concept. Challenges in the development of the space-borne optical interferometry have been studied and refined over a number of years. The resultant flight system reference design and configuration have been discussed along with some of the complex systems issues that require further study and trades. The SIM Flight System configuration is designed to meet all its' requirements, cost and schedule along with being able to deliver the scientific observations with unparalleled accuracy.

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