Space Interferometery Mission Starlight and Metrology Subsystems

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ABSTRACT

The Space Interferometry Mission (SIM), planned for launch in 2009, will measure the positions of celestial objects to an unprecedented accuracy of 4.0 micro arcseconds. In order to achieve this accuracy, which represents an improvement of almost two orders of magnitude over previous astrometric measurements, a ten-meter baseline interferometer will be flown in space. NASA challenges JPL and its industrial partners, Lockheed Martin and TRW, to develop an affordable mission. This challenge will be met using a combination of existing designs and new technology. Performance and affordability must be balanced with a cost-conscious Systems Engineering approach to design and implementation trades. This paper focuses on the Lockheed-Martin-led Starlight (STL) and Metrology (MET) subsystems within the main instrument of SIM. Starlight is collected by 35-cm diameter telescopes to form fringes on detectors. To achieve the stated accuracy, the position of these white-light fringes must be measured to 10^{-9} of a wavelength of visible light. The STL Subsystem consists of siderostats, telescopes, roof mirrors, optical delay lines and beam combiners. The MET Subsystem is used to measure very precisely the locations of the siderostats with respect to one another as well as to measure the distance traveled by starlight from the sidersostat mirrors and reference corner cubes through the system to a point very close to the detectors inside the beam combiners. The MET subsystem consists of beam launchers, double and triple corner cubes, and a laser distribution system.

1. INTRODUCTION

The Space Interferometry Mission (SIM), planned for launch in 2009, is a mission within NASA's Origins Program. SIM will be placed in an Earth-trailing solar orbit to measure the positions of celestial objects to an unprecedented accuracy of 4.0 micro arcseconds. After an initial six-month in-flight calibration and checkout period, the instrument will begin a five-year science mission to obtain highly accurate astrometric measurements of stellar objects. This mission will make measurements with far greater accuracy than is possible from ground-based observations. In order to achieve the 4.0 micro arcsec accuracy, which represents an improvement of almost two orders of magnitude over previous astrometric measurements, a ten-meter baseline interferometer instrument will be flown with pathlength changes in the tens of picometers being measured. Refer to Figure 1-1.

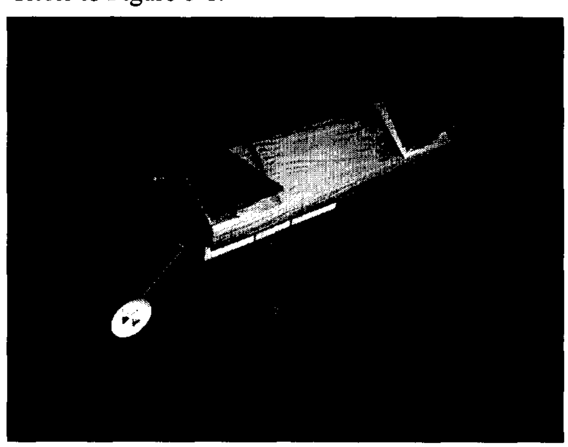

Fig 1-1 SIM Spacecraft (Courtesy TRW)

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The instrument consists of four major subsystems: Starlight (STL), Metrology (MET), Precision Support Structure (PSS) and Real Time Control (RTC). Three organizations are teaming to develop the SIM Flight System. JPL leads the overall system development and Real Time Control subsystem, while TRW has the responsibility for developing the avionics, structures (including the Precision Support Structure or PSS) and spacecraft. TRW is also responsible for the final spacecraft integration and test, or assembly, test and launch operations (ATLO). Lockheed Martin is responsible for the development of the instrument STL and MET subsystems as well as instrument integration and test (II&T). This paper focuses on the two STL and MET subsystems. As the program is currently in the "A Phase", the design is in the conceptual phase.

After a brief spacecraft/instrument overview and discussion of the major instrument requirements, the Starlight and Metrology subsystems will be discussed. These constitute the major optical elements of the instrument. Each subsystem delivers flight hardware to the program and deals with a plethora of inter-subsystem interfaces. Due to the stringent thermal and structural dynamic constraints, Graphite Cyanoacrylate (GrCy) is a likely choice of composite material for all precision structures including TRW's PSS.

The SIM design uses four co-linear interferometers mounted on a 10-meter long structure (see Figure 1-2). Each interferometer collects light and combines them together to form fringes. Two of the four interferometers, referred to as guide interferometers, will acquire fringes on bright guide stars in order to make highly precise measurements of the spacecraft attitude. The third interferometer, or science 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. The remaining science interferometer is a redundant spare and also can act as a guide interferometer.

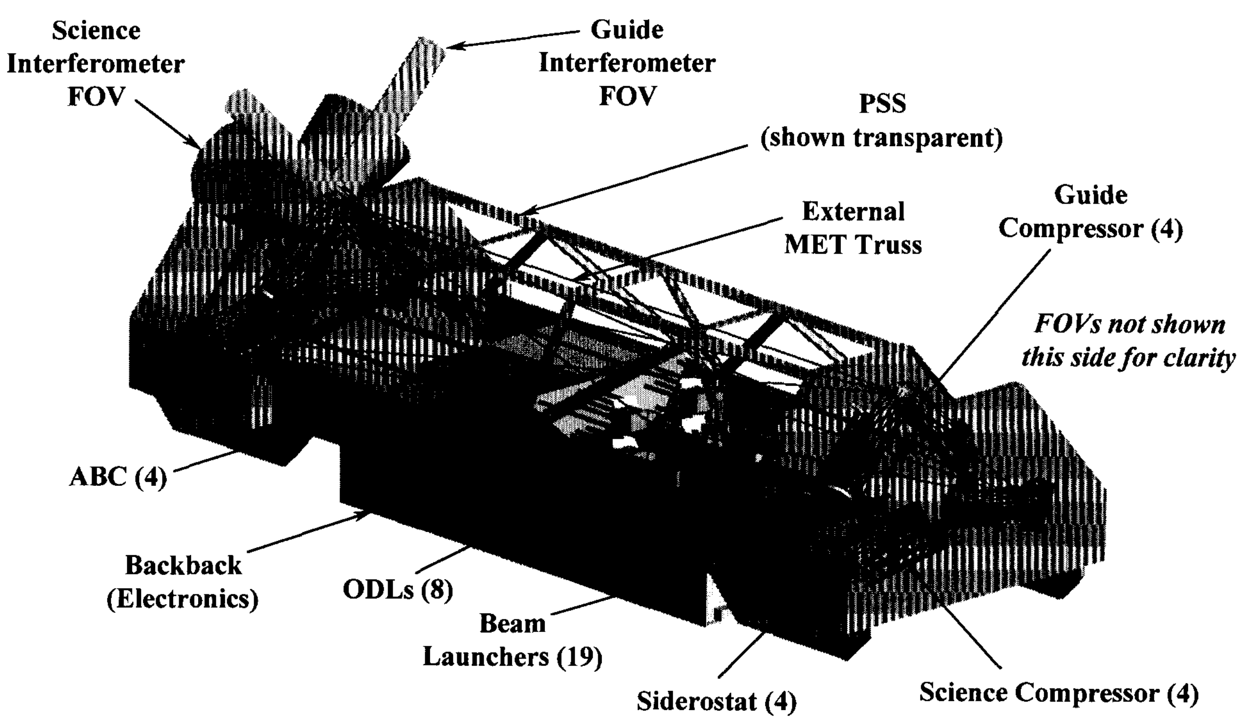

Fig 1-2 SIM Instrument

Since the science objects will typically be dim (18-20 visual magnitude), the attitude information from the two guide interferometers locked on "brighter" guide stars will be used to point the third (science) interferometer. 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 periods have been defined to support narrow-angle, wide-angle and reference-grid-closure astrometric objectives. The narrow-angle measurements require 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 up to two weeks at certain times throughout the mission.

2. FLIGHT INSTRUMENT CONFIGURATION

The two main optical subsystems within the SIM science instrument are Starlight and Metrology. Refer to figure 1-2. The Starlight (STL) subsystem is the primary science component of the interferometry instrument and essentially comprises all optics and sensors with which the starlight interacts. There are two Science baselines (for redundancy), and two Guide star baselines. The Guide star system tracks two known stars approximately 90 deg apart, while the Science system collects data on other stars within its 10 mrad FOV.

Metrology (MET) is the secondary, but essential, subsystem that keeps track of relative positions and orientations of all key optics. This is done by locating precise corner cubes at the center of key optics. Metrology knowledge at the tens-of-picometers level is necessary in order to reach the levels of precision required by SIM.

The STL and MET subsystems are comprised of many electro-optical components, and most are very difficult to implement due to the required precision in location, wavefront quality, and pointing. The main components include:

Starlight Subsystem
- Siderostats; steerable, large flats
- Beam Compressors; off-axis, 3-mirror, collimating telescope
- Fast Steering Mirrors (FSM)
- Fold Mirrors and Enclosure
- Optical Delay Lines (ODL)
- Astrometric Beam Combiner (ABC)
- Guide and Science Interferometer Sensors

Metrology Subsystem
- Metrology Optical Truss (configuration)
- Corner Cubes (CC)
- External Beam Launchers
- Internal Beam Launchers
- Laser Source

3. STARLIGHT SUBSYSTEM

The siderostats (Sids) are steerable, elliptical flats (50 X 40 cm) with a corner cube at their centers. They are the first elements that starlight sees as it enters the instrument, and they define the end points of the SIM interferometer. Refer to figure 3-1. Each Sid directs the starlight to the beam compressor and has a field-of-regard (FOR) of +/- 7.5 degs. The beam compressor is an off-axis, 3-mirror anistigmat (TMA), afocal telescope that reduces the incoming 35 cm starlight beam to 5 cm.

Next in the beam path, the fast steering mirror (FSM) accepts the starlight from the compressor and keeps the beam stable on the detectors, via a feedback loop driven by a quad cell near the focal plane with an effective bandwidth of 100 Hz. The beam path is then folded through a set of plano mirrors allowing both paired legs of an interferometer to have identical fold order, direction and path length.

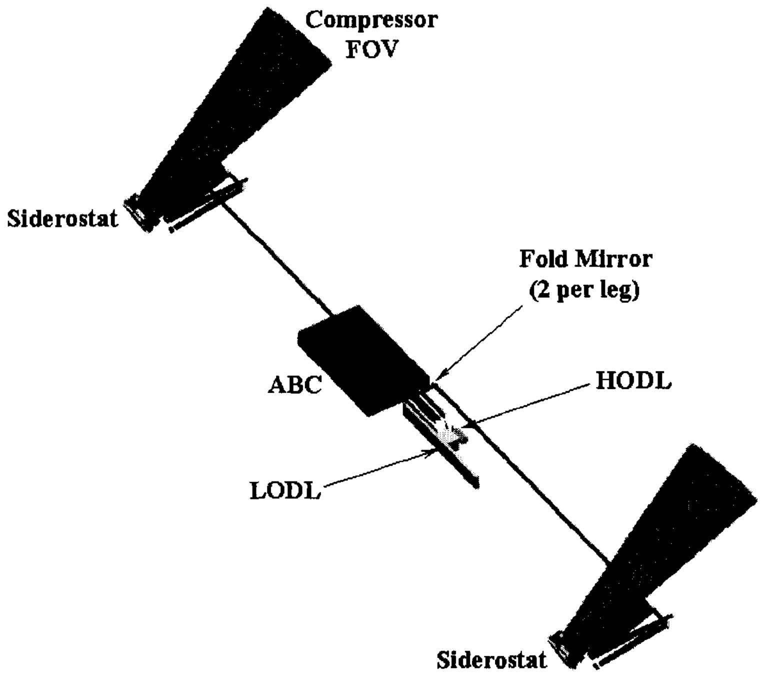

Figure 3-1 Single science interferometer optical layout

The low-bandwidth optical delay line (LODL) is a precision trombone structure that is used to equalize the path length of the starlight coming into the Sid in one leg to that coming into the other, in order to obtain white-light fringes in the interferometer. From the distance the LODL is driven, the angle between two stars being observed can be determined. Accordingly, LODL data is the key SIM data generated, after being adjusted for various error sources. The high-bandwidth optical delay line (HODL) resides in the paired interferometry leg and actively removes high frequency path-length changes due to structural and STL components.

The astrometric beam combiner (ABC) combines one pair of beams, along with several reference beams, for introduction into the white-light interferometer and other sensors. Both interferometers enable the taking of SIM science data by sensing white-light fringes. The Guide interferometers differ from the Science in that they contain no siderostats. Instead, the compressors in each bay are assembled into a common structure that tip/tilts $\pm$10 mrad.

3.1 Siderostat

The SIM Instrument has four siderostats that control the field-of-regard (FOR) for each of the four science compressors (telescopes). The siderostat mirror can be pointed in azimuth and elevation so that a 15-degree conical FOR is provided to the system. The optical device consists of a tip/tilt gimbal mechanism holding an elliptical-plano mirror with a corner cube (CC) mounted at its center.

Several difficult requirements drive the design of the siderostat assembly. In the center of each plano mirror sits a CC, whose vertex must lie on the same plane as the mirror surface to within 10 μm. Both rotational axes of the gimbal must lie on the plane of the mirror surface, pass within the 10 μm "tolerance sphere" and be perpendicular to each other to a similar order of magnitude. The rotational accuracy of the azimuth and elevation drives is 4 arcsec. These requirements are a direct flow down of the overall resolution of the system which requires a 4 μ arcsec angular resolution.

Keeping the CC centered on the siderostat mirror and maintaining the gimbal axes alignment will require a very stable thermal environment. The mirror will be mounted on bipod flexures to a bezel. An offset, radiatively-coupled heater plate will maintain the mirror and CC to room temperature and ensure that no gradient changes exceeding 2.5 mK/hr are generated. In addition, any motors used in the system will require low power dissipation when in motion as well as when they are locked in position.

In order to accomplish the requirements of this device, several existing and new technologies will be utilized. The positioning of the CC on the surface of the siderostat mirror will be key to the success of the system and this will be achieved through relatively new methods in optical element bonding. Bond joints and thermal characteristics play a critical role in the thermal performance of the system and will need to be well understood before a successful design can be implemented.

The mirror bezel will also act as the inner gimbal ring. It is likely that this ring as well as the outer gimbal ring will be manufactured from a composite material with metallic inserts. This will allow orthogonal pairs of rotary flexures to be laser welded to the rings with the use of precision tooling. Mechanical positioners capable of measurable sub-nano-meter movement and precision rotary encoders will also be required.

Structural materials with low mass, high stiffness, and favorable thermal characteristics will be sought after, with low or zero-CTE composites being the likely materials of choice. The plano mirror will be lightweighted, in the 65% range.

3.2 Compressor

Starlight is collected by a 35 cm diameter aperture, three mirror anastigmat compressor shown in figure 3-1. This compressor has a 1 by 0.1 degree unobscured field and provides a 7:1 afocal beam reduction. Other features of this system include an intermediate image, real exit pupil for stray light control and an optimized flat image plane for low distortion. The primary, secondary, and tertiary mirrors are general aspheres with a fold flat for packaging.

All optics will be manufactured from Zerodur due to extremely tight wavefront requirements involving thermal gradient changes in the milliKelvin range over an hour. The primary mirror will be lightweighted to at least the 65% level to keep the overall weight down and the metering structure will be GrCy. Both the science and guide compressors will be identical in prescription to keep costs down. However, it remains to be seen if the metering structures will be the same as their interfaces to supporting structure may be too different.

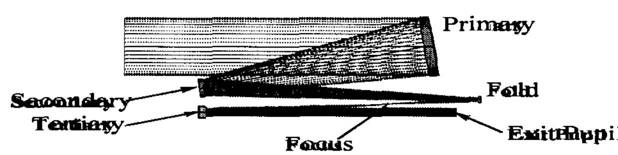

Figure 3-1.
Compressor Optical Raytrace

3.3 Fast Steering Mirror (FSM)

In order to produce sufficient fringe visibility and satisfy mission timelines, the relative tilt between the two arms of each interferometer must be maintained at less than 30 milliarcseconds (mas), 1σ, as measured on the sky. Since the FSMs are located in the compressed beam space, with a front-end compression ratio of 7:1, the beam widths handled by the FSMs are 5 cm (minor axis), and the true pointing requirement in mirror space is 210 mas or about 1 microradian.

The FSM mechanism operates in conjunction with a feedback signal provided by a CCD camera located in the astrometric beam combiner (ABC). The FSM suppresses tilt disturbances from several primary sources: residual uncompensated tilt errors from the siderostat pointing control loop, structural dynamic disturbances introduced mainly from the spacecraft reaction wheels, moving mechanisms located throughout the instrument, and sensor noise. In order to minimize self-induced disturbances the FSM is designed to be reaction-canceling. The current pointing loop design for SIM has sufficient sensitivity to provide centroided guide star position information from the CCD at a 1kHz sample rate, and to close the FSM pointing control loop at a bandwidth of 100 Hz.

The residual tilt error downstream of the SID is required to be less than 100 mas, 1σ. At the FSM, this is magnified by the compression ratio of 7, and by the number of standard deviations needed to guarantee that the FSM has sufficient control authority for an entire observation, perhaps 10. This would seem to impose a dynamic range requirement for the high bandwidth operation of the FSM to be on the order of 5-10 arc seconds. Initial alignment uncertainty, gravity release, outgassing of the structure, and thermal deformation expand this dynamic range to about 80 arc seconds.

The FSM also has an additional requirement of operating in 'auto collimate mode' for calibration purposes. In short, not only must the FSM provide the high-bandwidth tilt control for tracking stars, but it also must be capable of at least a single-axis (and possibly two-axis) large angle rotation so as to return a stimulus/calibration source, which originates in the ABC, back to the ABC so that diffraction, radiometrics, and other diagnostic and calibration tests may be performed on the Instrument.

The current design concept contains a plano mirror mounted within a bezel with three equally-spaced PZTs mounted behind the bezel to obtain the necessary tip/tilt function. This entire mechanism is carried on a single axis gimbal allowing the mirror to be rotated about its front surface, minimizing beam walk in the retro mode.

3.4 Fold Mirrors and Enclosure

The fold mirrors serve two purposes: 1) relaying the starlight beams from paired legs of each interferometer to a common astrometric beam combiner (ABC) and 2) maintaining the order, angle, length and direction of each leg so they are identical, preventing polarization and pupil geometry differences.

Maintaining identical optical folding parameters for pair lengths is of paramount importance. Not doing so would cause insurmountable errors when the two legs are combined, since polarization and pupil geometry consistency are necessary to obtain high-contrast fringes. Having identical beam path lengths from the compressor primary mirrors to the ABC beam splitter allows the optical delay lines (ODLs) to be positioned at mid-range when the starlight FORs are at their mid-range.

The configurational of a single science interferometer can be seen in figure 3-1. Note that both legs fold identically in order, angle and direction. The beam lengths from one mirror to the next need not be matched but the total path length from the compressor primary mirrors to the ABC must be within a few millimeters of each other.

The fold mirrors for the –Y bay interferometer legs are contained within the bays while those mirrors for the +Y legs are housed within the fold mirror enclosure positioned between the ABCs and ODLs. The fold mirrors were strategically placed, allowing all relaying requirements to be met along with the benefit of being housed within a Starlight structure.

The relay mirrors are plano and, to maintain the wavefront requirement of lambda/100, will need to be flexure-mounted with radiatively-coupled heater plates. The enclosure will be manufactured from GrCy and will attach to the PSS through three kinematic mounts.

3.5 Optical Delay Lines

Just as there are requirements on the pointing system for guaranteeing sufficient fringe visibility, equally, if not more, demanding requirements are imposed on the path-length control. The requirement for path-length control is 10 nm, 1σ. Path length disturbances are due to reaction wheels, self-induced mechanism motion, sensor noise, and spacecraft attitude motions. The attitude control system (ACS) of the spacecraft on which the instrument is mounted introduces low frequency (0.01 Hz - 0.1 Hz) rigid body motion of 2 arc seconds, 1σ, even during an observation. For a 10-meter interferometer baseline, this attitude motion results in path-length deviations of 100 microns, which must be controlled to the sub-10 nm level for proper operation of the interferometer. To guarantee sufficient range the delay line dynamic range has been selected to be 2 mm.

Analyses have shown that a full beam width, racetrack corner cube (CC) is required to avoid introduction of wavefront curvature. "Racetrack" refers to the path a beam of light travels going between two CC: the entire beam hits each of three mirror surfaces on each CC, tracing a racetrack pattern. The current baseline for this mechanism is a reaction-canceling CC that provides the entire dynamic range needed for the high-bandwidth path-length control. The current mechanism concept for the high bandwidth optical delay line (HODL) has the CC mounted to axially-positioned disk flexures, driven by a voicecoil. The voice coil reacts against a reaction mass. The feedback signal is derived from a fringe tracker that is located in the ABC. The HODL, e.g., modulates the optical path approximately 1 wave at 250 Hz, and uses a dispersing element in conjunction with the path length modulation to ascertain the position of the starlight fringe position to better than 10 nm.

The SIM instrument also has a field-of-regard (FOR) of 15 degrees. Once locked onto a pair of guide stars, the science interferometer observes stars anywhere within this field of regard. With a 10 m baseline, this means that an optical path difference of almost 2.5 meters must be made up with the low bandwidth optical delay line (LODL).

With a reflective optic, only half of this range must be produced by the mechanical system. Nonetheless, this still presents formidable challenges. Fortunately, based on the observation scenarios, one knows well in advance the proper location for this large motion delay. The LODL will be a precision stage, designed to move a racetrack CC at 10-cm/s. This speed is based on multiple science gathering requirements. The CC travel must be controlled in its transverse motion to several microns to prevent the introduction of beam walk errors. This controlling mechanism may be a PZT-driven device. Once in the correct linear position, the CC will be locked into position for the entire observation. The remaining errors are then removed by the actively-controlled corner cube optic (HODL).

3.6 Astrometric Beam Combiner

The compressed starlight wavefronts propagating through the system pass from the ODLs into the astrometric beam combiner (ABC). Within the ABC, the starlight input is split into two paths to perform angle and fringe tracking functions. The ABC also houses the internal metrology assembly and the internal calibration optics.

There are four ABCs in SIM, two serving the guide interferometers and two serving the science interferometers; a single design meeting the more stringent science interferometer requirements is being used for all four ABCs. This results in the ABCs being somewhat "over-qualified" for the guide interferometers, but a net savings should be realized in design, development, fabrication, assembly, and test costs.

The layout of the ABC is illustrated to scale in figure 3-2. The enclosing red box indicates the volume allocated within the overall SIM instrument for the ABC. The design to date has considered primarily the first order optical requirements. Since the light is collimated for a majority of the path, there is flexibility in the placement of many of the ABC elements. Some additional space can be provided in specific areas if it becomes necessary, once the detailed mechanical and thermal designs are explored.

The light-generating sources are located in the instrument backpack, and their outputs carried to the ABCs by fiber optic cables. The fiber outputs are collected and collimated in two places: the internal metrology assembly, and the self-check and calibration source. The internal metrology beam is introduced into the system via a hole in a fold mirror. It is split into a core beam and an annular beam in the compensated combiner; each beam then propagates through the system to a compressor fiducial, and then returns it back to the ABC. When activated, the self-check and calibration beam is injected via a non-polarizing 90/10 beamsplitter; it then propagates to the compensated combiner where it is split into two beams. Depending on the exact arrangement of retro shutters, starlight shutters, siderostat and FSM orientations, these beams are used to verify the internal operation of the ABC and alignment of the starlight paths, and support diffraction calibration of the system.

The light in each arm entering the ABC first encounters separate non-polarizing 50/50 beamsplitters, splitting the light into angle-tracking and fringe-tracking paths (via transmission and reflection, respectively). The angle tracker camera consists of four opto-mechanical paths, forming four distinct, non-overlapping spots on two array detectors (a CCD for the 0.4-0.9 μm starlight, and an IR array for the internal metrology light) mounted to a common interface. By determining the centroid of the starlight spots with respect to the internal metrology spots, information about the angle of the light paths within the SIM instrument can be inferred, and used to control tip/tilt commandable elements at other locations within the optical paths.

The fringe path contains the compensated combiner, which consists of three plane-parallel refractive plates to compensate for first-order misalignment and chromatic effects, and the combining beamsplitter. A pattern of masks and coatings on the combining surface serves to interfere the starlight beams (forming two outputs) and splits the internal metrology beam (and the self-check and calibration beam when activated).

The internal metrology laser light propagates into the internal metrology assembly for heterodyne detection. The two interfered starlight combiner outputs propagate to a 10x confocal parabola compressor with a 2 arcsec (as measured on the sky) field stop. The light is then dispersed and focused onto a CCD detector, with a slight offset in one of the paths to create two distinct fringe spectra on the CCD.

When the self-check mode is in effect, the various shutters are opened and closed to selectively illuminate the CCRs and all or part of the optical paths of the ABC, and thereby verify the functioning of the detectors and associated electronics.

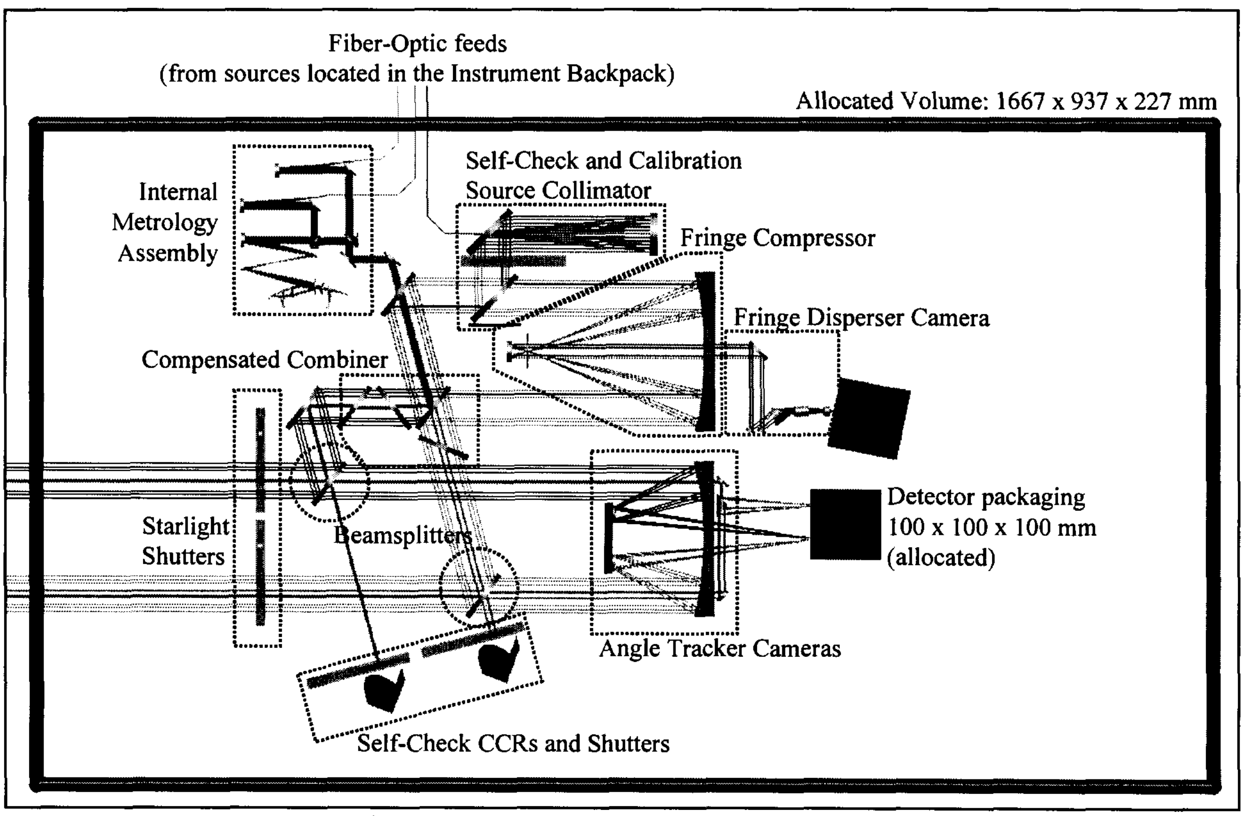

Figure 3-2. Astrometric Beam Combiner

3.7 Bays and Interfaces with PSS

At both ends of the PSS are two large bays containing what is referred to as the front end optics: guide and science compressors, siderostats, fast steering mirrors and external metrology corner cubes. Refer to figure 3-1. Each bay is a self-contained structure allowing for ease in assembly, unit testing and PSS integration.

The bay structure is manufactured from GrCy for metering stability and high strength. To obtain thermal stability, the bay is open to deep space, thereby giving the movable optics a significant view factor. This minimizes thermal gradient shifts due to siderostat and guide compressor pointing changes. The outer walls of the bay view the PSS inner surfaces. The bay inner walls are covered with multi-layered insulation

(MLI) consisting of multiple sandwiched layers of alternating mylar, with double-sided aluminum evaporated coating, and fine silk netting. The outermost layer "sees" deep space and will passively maintain itself at 150K through radiative coupling.

All optics within the bay will be bias-heated to 293K through backside, radiatively-coupled heater plates. This will allow all optics to operate at the temperature at which they were manufactured and tested, maintaining milliKelvin (mK)-class gradients, preventing figure changes that would cause unacceptable beam walk errors.

The bay structure will consist of a base, acting as an optical bench for all optical components, and carrying all loads to the PSS. Lightweight sides will close out the bays allowing the PSS to maintain its own thermal stability and cleanliness. In addition, the sides support the inner surface MLI. The current alignment requirements placed on the bays necessitate tip/tilt actuator adjustments of ± 2.0 mm at three points. These actuators will be linear ball/nut drive types and flexures will carry the lateral loads.

4. METROLOGY SUBSYTEM

Figure 4-1 shows the metrology truss configuration. The purpose of the truss is to precisely track the physical relationship (3-DOF) between each pair of nodes. This knowledge is essential to eliminating error sources in the science data. Each node contains a retro reflector, which may be single, double, or triple corner cubes (CC), as required. For instance, since any one retro has an acceptance angle of +/- 30 deg max, node 2 requires a triple, which consists of 3 precise corner cubes with a common vertex.

The truss members are optical links only (no structure). Each link (blue line) contains at least one beam launcher. A beam launcher is a device that sends out a laser beam which makes a circuit between two nodes, takes in the return, and interferometrically measures changes in path length against a reference beam. Heterodyne interferometry is used for greater precision. These units must be sensitive to changes in the 10 pm regime, a few millionths of a wave.

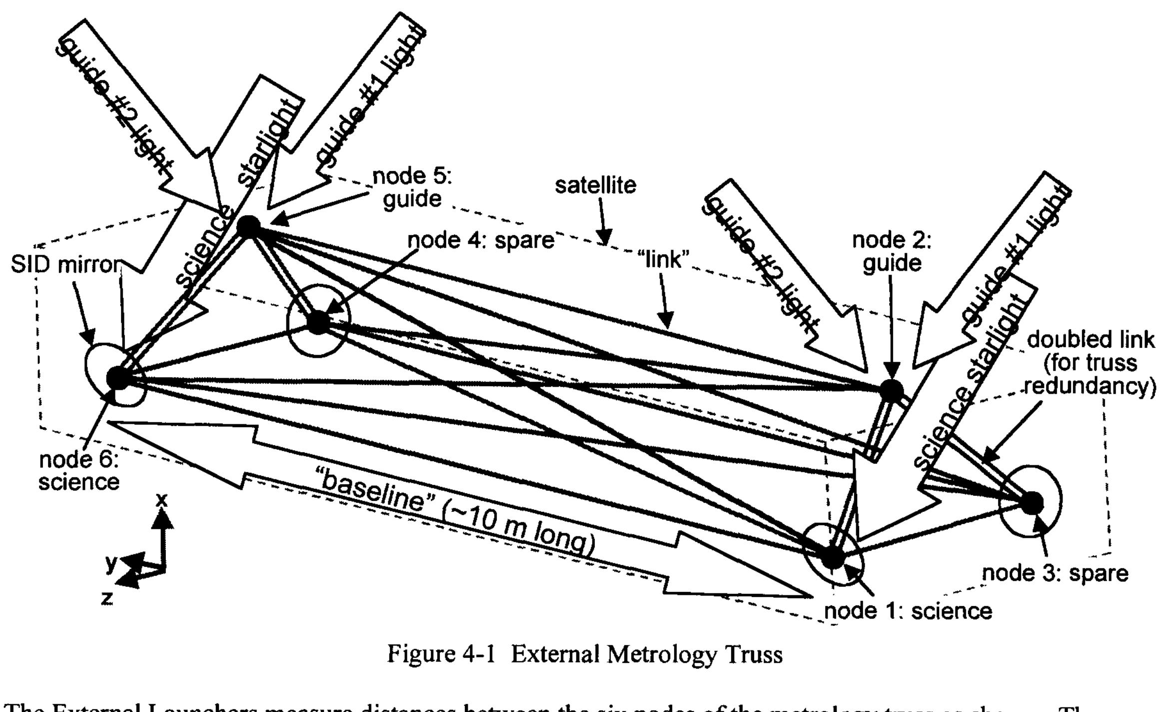

Figure 4-1 External Metrology Truss

The External Launchers measure distances between the six nodes of the metrology truss as shown. The bottom four nodes represent the centers of the science Sids, and the upper two represent the "centers" of the guide star sensors. Knowledge of this truss provides the framework for the SIM instrument.

Internal Launchers are used to measure distances that the starlight traverses within the instrument, in order to compensate for differences in path length being introduced by the science instrument itself. The laser sources are highly stable reference beams in the 1.3 – 1.5 micron range, with about 30 mW power.

4.1 External Metrology Configuration

The PSS will be designed to be extremely rigid, but it will bend and stretch at the micro-arcsecond and picometer level. The purpose of the external metrology subsystem is to monitor the orientation of the science baseline with respect to the guide baseline, so that the flexing of the PSS can be backed out of the star measurements.

There are six "nodes" in the external MET structure to generate a metrology truss (see Fig. 4-1): the two ends of the science baseline (siderostat mirrors - SIDs), the two on the spare baseline SIDs, and two shared between pairs of compressor telescopes that stare at the guide stars.

To mathematically determine the relative (x,y,z) coordinates of *n* nodes requires at least ($n\times3$)-6, or twelve, links (measurements made between nodes by metrology gauges). Thirteen non-degenerate (e.g., not all coplanar) links can give redundant information that provides "error detection": the node positions are determined by a least-squares fit rather than explicit calculation, and the quality of the fit indicates whether all of the metrology gauges on the links are functioning correctly. Also, thirteen links can allow the truss to function even if a gauge fails (i.e., the truss is "fault tolerant"). However, it takes at least fourteen links (and at least four non-coplanar links to each node) to provide "error correction": the ability to not only determine an error in the metrology truss, but to identify and isolate the defective link.

There are fifteen possible pairings of nodes. The link between the two ends of the science baseline can't be made during science gathering as the SID mirrors block the gauge's view of the nodes. Only when the SID mirrors are tilted towards one-another in cross-eyed fashion, can the gauge "see" the node. The spare baseline can normally be cross-eyed providing the fourteen links needed for error-detection/error-correction, and the science SIDs can go cross-eyed for a routine self-check calibration or when the spare baseline is needed.

The shape of the external metrology truss, and the spacecraft instrument as a whole, results from various constraints: parallel baselines; overlapping compressor FOR; 3-D geometry for out-of-plane measurements; and the orientation and acceptance angles of the retro-reflectors, or corner cubes (CC), at the nodes as the SID mirrors are tilted over the full FOR.

To provide increased truss redundancy, four of the links are doubled-up (as shown), with two gauges measuring those links. The resulting "L15x+4" configuration enables error-detection/error-correction even in the event that any one gauge fails. As these doubled-links are nearly aligned with the direction of the science and guide starlight as it enters the instrument, this also provides for a very robust truss configuration with precise measurements of the most critical dimensions.

4.2 External MET Beam Launcher

A laser interferometer consists of three main components: (1) the laser source, including the modulators that create the two frequency-shifted laser beams; (2) the "beam launcher", which collimates, folds, launches, collects, and mixes the laser beams; and (3) the signal processing: detectors, amplifiers, A/D converters, phase meters, etc. The external metrology truss is comprised of a number of interferometers (all powered from a single laser source, so that any laser drifts cancel in common-mode), along with a number of retro-reflectors (the fiducials that form the nodes of the truss) and some pointing control hardware (to keep the laser beams aligned with the retros in case the satellite warps too much).

JPL and Lockheed Martin have been collaborating for a number of years to develop the "perfect" beam launcher, one that can measure distances at a resolutions ten picometers. After several iterations, the designs are getting quite good, as each incorporates the "lessons learned" from the previous iterations. The latest design known as "QP" (or "Quick Prototype") beam launcher was developed to test and verify some of the past lessons.

To get the sub-nanometer accuracy demanded by the SIM project, every error source needs to be considered, even those normally discounted as "negligible" or "second order". This impacts the design of the laser source and the signal processing, but the principal area for improvement is in the beam launcher.

The interferometer is in the heterodyne configuration, because even minor intensity fluctuations in laser power give unacceptably large phase shifts in the alternative homodyne configuration. Refer to Figure 4-2.

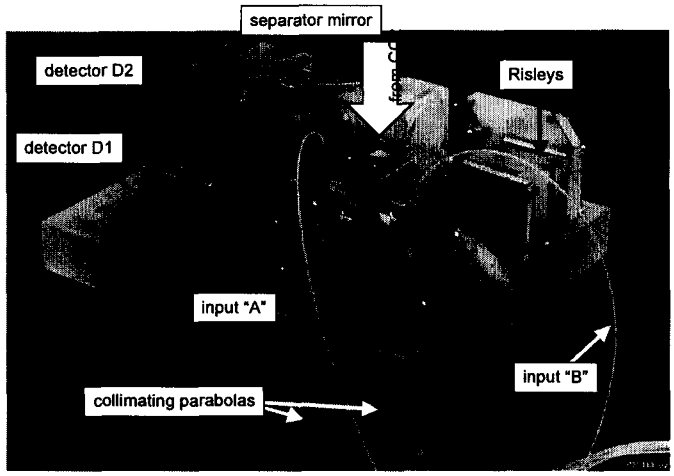

Figure 4-2. Quick Prototype (QP) Beam Launcher

4.3 Laser & Distribution

The metrology light supplied to the beam launchers is comprised of two beams at 1.319 microns, separated in frequency by 100 kHz (TBD), which are the heterodyne beams for relative phase measurement. The source for this light is a Nd:YAG non-planar ring oscillator (NPRO) laser. The laser light is split, and the two beams are each frequency shifted by AOMs, so the difference frequency is controlled by the RF oscillators which drive the AOMs. Additionally, a second laser is offset locked to the first laser at a difference frequency of 15 GHz for absolute metrology. In absolute metrology, the input to the heterodyne AOMs is toggled between the two lasers. In relative metrology, only one of the lasers is used. A schematic of this is shown in Figure 4-3.

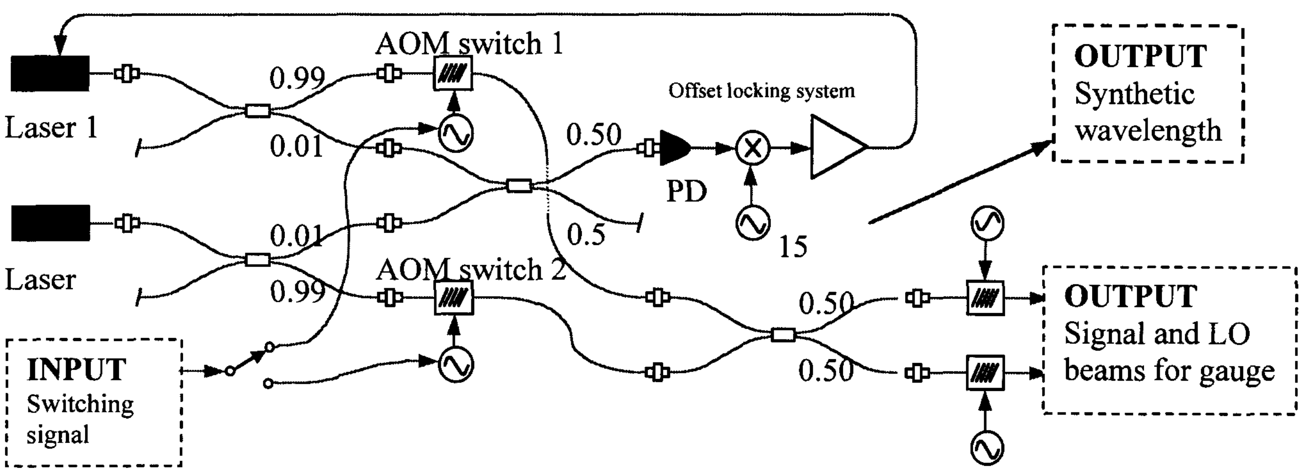

Figure 4-3. Distribution Schematic

4.4 Corner Cube Development

Hollow Corner Cubes (CCs) are used in several places within the MET subsystem: guide interferometer fiducials (2) and science interferometer siderostat fiducials (4), not to mention those located within the ABCs for internal metrology. The requirements for these optical elements are pushing the state-of-the-art in both optical and geometry areas. While the siderostat-mounted CCs are single types, the guide interferometers require double CCs due to widely separate FOVs.

The development of corner cubes, in support of the SIM program, investigated domestic and foreign suppliers. The initial test articles are to be used for characterization of SIM launchers in a two-gauge test configuration. Based on this development phase, prototype and flight composite structures, consisting of a SID mirror and wedged optical elements, are to be created.

The initial corner cube design contains three reflective surfaces supported by an interface. Parent material choices have mainly been limited to Zerodur or ULE for stability and CTE related issues, with no constraints on weight or size. Input from suppliers responding to an RFI has identified four limiting factors: wavefront error, interface gap, reflective coatings, and orientation of a reference flat (simulated SID mirror surface) to the corner cube's vertex.

Wavefront error quality better than $\lambda/200$ rms ($\lambda/50$ p-v) was limited by fabrication, configuration, and coating processes. Relaxation of coating, entrance beam diameter, and parent material requirements were identified as possible parametric trades to achieve wavefront errors of $\lambda/500$ rms ($\lambda/125$ p-v). Maintaining the wavefront error quality is essential to minimizing errors in the measured and reference beams.

Interface gaps, where the double CC wedged optical element vertexes nearly touch, of less than 5 μm are constrained by fabrication and integration processes. There are also concerns identified with facet edge damage due to thermal and mechanical stress, as well as being able to verify gap dimensions. Solutions to these issues lie in potential design interfaces between facets, new fabrication and integration processes, and measuring techniques for dimensional verification. Minimizing the interface gap will reduce phase error contributions in the SIM design.

Coating constraints were due to handling concerns and fabrication steps that required coating reflective surfaces after facets had been fused. These issues are not perceived as design limiting in nature. Likewise, orientation of the corner cube's vertex appears to be an issue of design maturity.

5. SUMMARY AND ACKNOWLEDGEMENTS

The SIM instrument is possibly the most technically challenging optical instrument scheduled to be flown in this decade. Only through continued dedication of the scientists, engineers and subcontractors on this program can it possibly succeed. The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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