The Space Interferometry Mission (SIM): Technology Development Progress and Plans

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Abstract—Optical and infrared interferometry will open new vistas for astronomy over the next decade. Space based interferometers, operating unfettered by the Earth's atmosphere, will offer the greatest scientific payoff. They also present the greatest technological challenge: laser metrology systems must perform with sub-nanometer precision; mechanical vibrations must be controlled to nanometers requiring orders of magnitude disturbance rejection; a multitude of actuators and sensors must operate flawlessly and in concert. The Jet Propulsion Laboratory along with its industry partners, Lockheed Martin and TRW, are addressing these challenges with a development program that plans to establish technology readiness for the Space Interferometry Mission by end of 2004.

Keywords: interferometry, metrology, pointing, control, nanometer, picometer, optics, lasers

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1. INTRODUCTION

The Space Interferometry Mission (SIM), with a target launch date of December 2009, will be one of the premiere missions in the Astronomical Search for Origins (ASO) Program, NASA's bold endeavor to understand the origins of the galaxies, of planetary systems around distant stars, and perhaps the origins of life itself. This adventure of discovery will be enabled by an explosive growth of innovative technology, as exciting in its own right as the underlying scientific quest.

Over the past several years a consensus has formed around the idea that space based optical interferometers operating in the visible and infrared wavebands represent the next great leap forward in astronomy and astrophysics. Interferometers lend themselves to space application due to their extremely efficient use of weight and volume to achieve the goals of high resolution, high sensitivity imaging and astrometry. SIM (see Figure 1) will mark NASA's first scientific use of this revolutionary observing technique in space. If it succeeds, it will presage the flight of the Terrestrial Planet Finder (TPF) and other larger and more ambitious Origins interferometers.

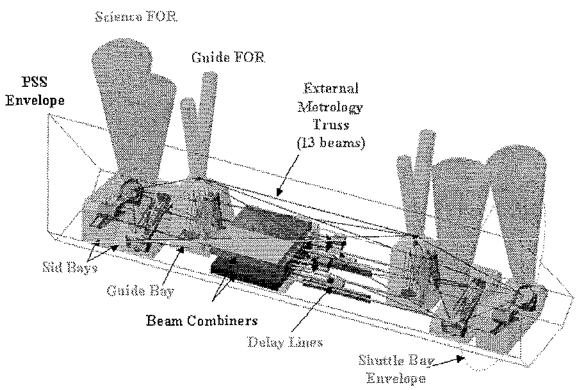

Figure 1 – CAD Rendering of SIM

SIM's premier science will be the identification of extra solar planetary systems. Figure 2 depicts the "discovery space" that will be opened by SIM on a plot of planet mass vs orbital semi-major axis. To date, all confirmed extra solar "stellar companions" have been discovered via the radial velocity technique which measures stellar doppler shifts at the 10 m/s level and thereby infers the presence of a planet or companion. The currently known set of companions is indicated on the figure by up-arrows. The arrows are pointing out a limitation of the radial velocity technique: since the inclination of the planet's orbit is indeterminate, the mass of the discovered object is only a lower bound. This makes it difficult to reasonably characterize the discovery as a planet instead of, say, a brown dwarf. Another limitation of the radial velocity

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method, as indicated by its "discovery line" on the plot, is that it can only hope to discover a sub-Jupiter mass planet if that planet is extremely close to the star. Astrometric instruments such as SIM are not limited to the discovery of these "pathological" solar systems. The discovery space opened by three astrometric interferometers, the Palomar Testbed Interferometer (PTI), the Keck Interferometer, and SIM, is depicted by the set of V-shaped curves. Notice that SIM improves, by orders of magnitude, the sensitivity needed to discover planets like those of our own solar system (which appear on the plot as E=Earth, J=Jupiter, etc.).

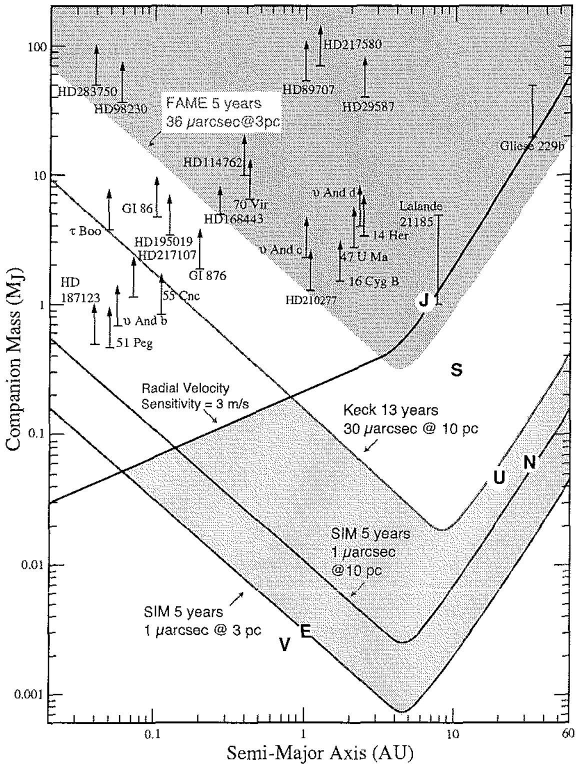

Figure 2 – SIM Extra Solar Planet Discovery Space

It is not surprising that such a huge step forward in observational power requires a concomitant leap in technological sophistication. SIM indeed drives the state-of-the-art in optomechanical and optoelectronic systems as well as presenting daunting challenges in precise stabilization of lightweight deployable structures and coordinated computer control of numerous optical surfaces. In this sense it very much embodies the principles of the Origins program—to couple breakthrough science with breakthrough technology in the service of both a fuller knowledge of our universe and a richer technological landscape that helps preserve our nation's preeminence as a force for global innovation. In this regard technology has become an important end-in-itself for NASA's Origins missions.

2. Major Technical Challenges

This paper proceeds by discussing the key technical challenges faced by SIM and the technology development approach to meet them. As an overview paper, there is appended an extensive list of references which contain greater technical detail on the various elements of interferometry technology.

Successful development of SIM requires that three grand technological challenges be met and overcome:

(1) nanometer level control and stabilization of optical elements on a lightweight flexible structure
(2) sub-nanometer level sensing of stellar fringe position and optical element relative positions over meters of separation distance
(3) overall instrument complexity and the implications for interferometer integration and test and autonomous on-orbit operation.

These flow from the fundamental science objectives of the mission.

The need for nanometer control is driven by requirements on fringe visibility for astrometry, which translate into the need for 10 nanometer RMS OPD control.

The picometer regime fringe detection and metrology requirements flow directly from the principal astrometry science requirements. For example, in order to make a 1 microarcsecond angular measurement between two stars using a 10-meter baseline interferometer requires the measurement of optical fiducial positions to about 50 picometers.

The complexity of an interferometer, with all its moving parts and control systems, is the price that must be paid for stepping beyond the paradigm of rigid monolithic telescopes as built since the days of Galileo. SIM will have to use active feedback control for at least 50 optical degrees of freedom. Another roughly 50 degrees of freedom will need to be controlled in open loop fashion. Additional degrees of freedom will require articulation at least once for initial deployment and instrument alignment. All of this places great importance on the development of realtime software capable of autonomously operating SIM. New and creative integration and test methods will also be required to enable development of the instrument at an affordable cost.

The suite of new technologies that must be developed to enable SIM is depicted in Figure 3.

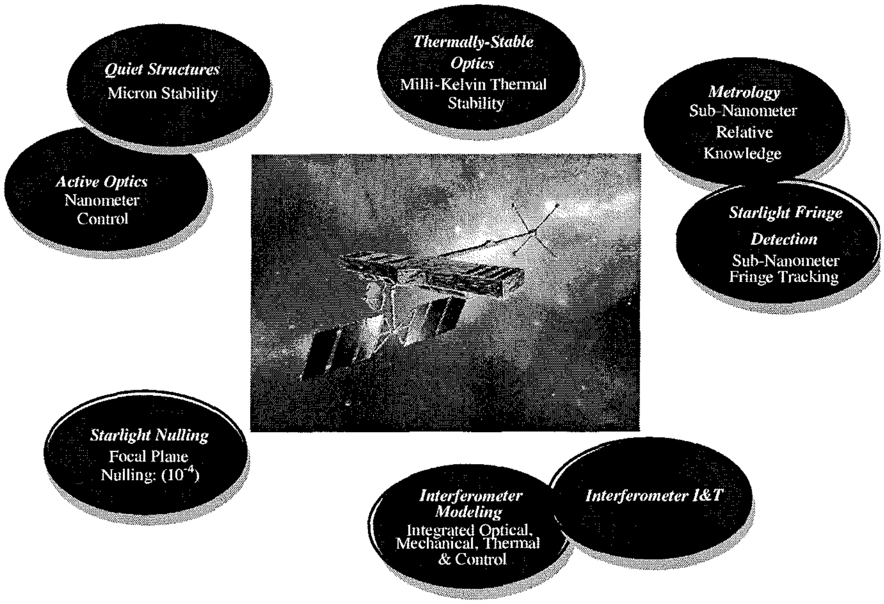

Figure 3 – Key Technologies for SIM

3. Technology Development Approach

Fundamentally the approach taken to technology development is one of rapid prototyping of critical hardware and software followed by integration into technology testbeds where critical interfaces can be validated, system level performance demonstrated, and integration and test procedures developed and verified. To some extent, due to the objective of completing the technology development by the end of 2004, this will entail concurrent engineering (e.g., we will need to develop some hardware component brassboards in parallel with the development of the testbeds, dictating that breadboards of those components will be used in the testbeds rather than brassboards, which would be preferred).

This approach places the ground testbeds at the very heart of the technology development effort. It is in these testbeds that the technology products will be validated and technology readiness demonstrated. It is also in these testbeds that our engineering team will learn about what works and what does not when it comes to integrating and testing interferometers.

3.1 Component Hardware Development

Breadboards and brassboards of the new technology components required by SIM will be built and tested by the technology program. The objectives are threefold: mitigate technical, schedule, and cost risk associated with key hardware components early in the SIM project life cycle (when the cost of correcting problems is low); deliver necessary components to the technology integration testbeds; transition the capability to manufacture the components to industry.

Note that only those components considered as high risk will be built and tested as brassboards. Figure 4 depicts the optical delay line that has finished development, performance and environmental testing.

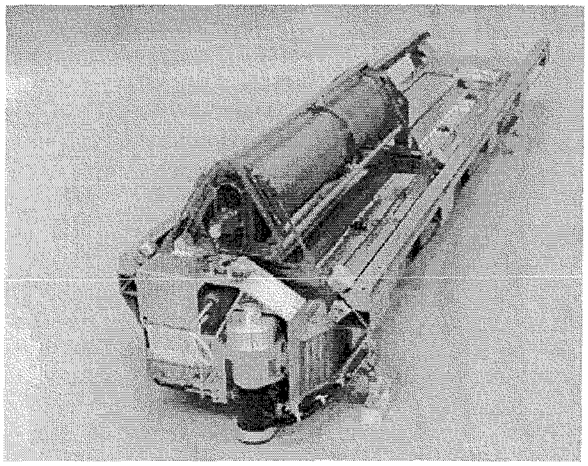

Figure 4 – Brassboard Optical Delay Line

3.2 Prototype Realtime Software Development

Space interferometers will be required to operate with limited intervention from the ground and in doing so perform initial optical alignment, calibration, stellar target acquisition, angle tracking, fringe tracking, slew, continuous rotation for synthesis imaging, and other autonomous functions. Realtime software will play the central role in performing these functions. This software represents a significant technical challenge since it will have to operate a very complex instrument, run on a distributed set of computers, and control processes at timescales from milliseconds to days. As advanced systems demand increasingly sophisticated software, the portion of project cost (and associated schedule and cost risk) assigned to software begins to rival that of hardware. Hence, the technology program has determined to place the importance of the development of realtime software on a par with that of interferometer hardware.

The approach to realtime software development is completely analogous to the development of component hardware via breadboards and brassboards. "Breadboard" software is regarded to be code that establishes the feasibility of performing a particular function. "Brassboard" software is a true prototype of flight software and demonstrates that the constraints imposed by the target flight processor can be met and that the code is efficient and maintainable. It is intended that the brassboard (or prototype) software developed under the technology program could actually be flown on SIM with only minor modification and upgrade required.

The job of developing SIM breadboard software is largely already done thanks to the development of two ground interferometers in recent years: the Palomar Testbed Interferometer (PTI) and the Micro-Precision Interferometer (MPI) Testbed. PTI and MPI share a significant amount of common realtime software and together demonstrate the basic feasibility of automated interferometer operation.

The development of the SIM prototype (or brassboard) software takes place in a development environment called the Realtime Interferometer Control Software Testbed (RICST). RICST builds the code in a modular fashion and is making a series of incremental deliveries. This greatly simplify the process of testing and debugging. The initial deliveries were internal to the RICST team and served to validate the development approach and train the personnel. RICST testing incorporates breadboard and brassboard hardware allowing the software to be fully exercised by actually driving the relevant controlled components. RICST software is being incrementally delivered to integration testbeds (described below) where it is being used to operate complete interferometers like SIM. This process is expected to result in software that can be referred to as "protoflight"—ready for flight application with modest rework.

3.3 Integrated Modeling Tool Development

The challenges facing space interferometry do not lie exclusively in the province of developing component hardware and realtime control software. Work is also needed to advance the state-of-the-art for software tools for analysis and design. Existing analysis tools provide only limited capability for evaluation of spaceborne optical system designs. They determine optical performance from the geometry and material properties of the optical elements in the system, assuming only minor deviations from the nominal alignment and figure. They cannot evaluate the impact on optical performance from controlled/ articulated optics, structural dynamics, and thermal response, which are important considerations for future interferometer missions. To investigate these critical relationships, a new analysis tool has been developed called Integrated Modeling of Advanced Optical Systems (IMOS). IMOS enables end-to-end modeling of complex optomechanical systems (including optics, controls, structural dynamics, and thermal analysis) in a single seat workstation computing environment. IMOS has been applied at JPL to the Hubble Space Telescope and the Space Infrared Telescope Facility (SIRTF), as well as virtually all the space interferometer designs that have been considered in recent years (e.g., SIM, OSI, ISIS, SONATA, DLI, FMI, MPI, POINTS).

IMOS was originally created as a modeling tool to assist in the early design phases of multidisciplinary systems. In recent years IMOS has matured tremendously and has greatly increased its ability to address complex, many degree-of-freedom systems that are typical of the detail design phase. Currently IMOS is the baselined integrated modeling tool for the SIM project and NGST pre-project, and is also being adopted by their industrial partners. Figure 5 shows a thermal/mechanical analysis run in IMOS predicting the deformation of one of SIM's collector telescopes over expected temperature changes.

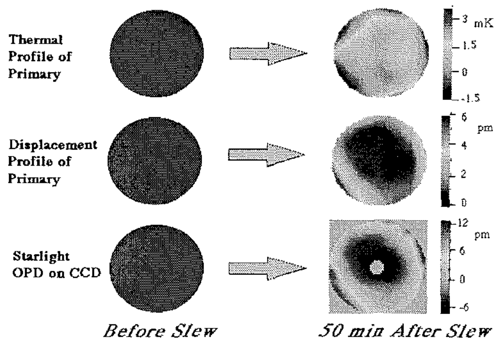

Figure 5 – Collector Deformation Map Over Temperature

3.4 Ground Integration Testbeds

Optical interferometry is not yet sufficiently mature to allow us to assure system performance on the basis of an exhaustive set of component tests. Rather it is necessary at this point to do validation testing at higher levels of integration to prove the technology is ready. This is the province of the ground testbeds.

Three major ground testbeds are planned: the evolutionary SIM System Testbed (STB-1,3), the Microarcsecond Metrology (MAM) Testbed, and the Flight Astrometric System Testbed (FAST). This particular delineation of the ground testbed effort derives from the recognition that one major subset of the technologies can be tested in air at nanometer precision and at full scale while another subset must be tested in vacuum at picometer precision but at subscale. The first set of technologies, i.e., those associated with vibration attenuation, is grouped into the STB. The second, i.e., the laser metrology technologies, is assigned to the MAM Testbed and FAST. FAST is currently in the early design phase and will not be discussed further in this paper.

SIM System Testbed (STB)—The SIM System Testbed is actually an evolutionary series of two testbeds. The first, STB-1, was built during the FY'91 through FY'94 timeframe. It is a full single baseline interferometer built on a flexible structure (see Figure 6) out of breadboard hardware components.

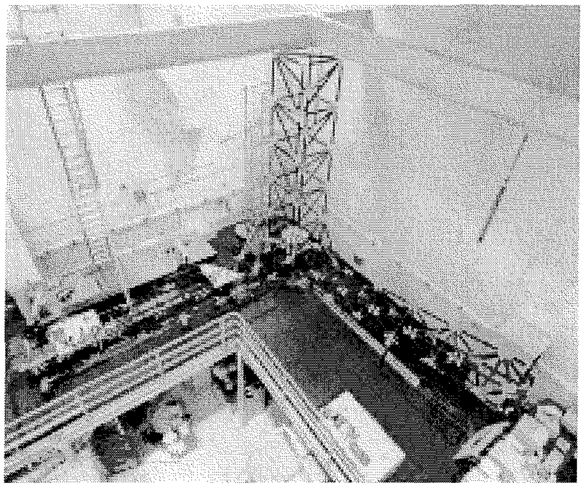

Figure 6 – Bird's Eye View of STB-1

The structure is a 7m × 6.8m × 5.5m aluminum truss weighing 200 kg (with optics and control systems attached the weight is about 600 kg). Three active gravity off-load devices make up the structure's suspension system providing about a factor of ten separation between the structure's "rigid body" and flexible body modes (the lowest of which is at about 6 Hz). The equipment complement includes a three tier optical delay line with associated laser metrology, a pointing system complete with two gimballed siderostats, two fast steering mirrors, and coarse and fine angle tracking detectors, a six-axis isolation system, and all associated electronics and real time computer control hardware necessary for closed loop system control and data acquisition. The principal objectives of STB-1 are demonstrating vibration attenuation technologies and validating the IMOS modeling tool in the nanometer regime. STB-1 was completed during the summer of 1994 when "first fringes" were acquired. Two metrics have been tracked over time to monitor testbed progress. These are: (a) pseudo-star fringe tracking stability in the presence of the laboratory ambient vibration environment and; (b) fringe stability vs. emulated spacecraft reaction wheel disturbances, which are expected to be the dominant on-orbit disturbance source. The current performance, as measured by each metric, is below 5 nm RMS (see Figure 7 for a typical lab ambient fringe tracking time trace).

Recent experiments have been conducted utilizing a flight spare reaction wheel as the disturbance source rather than using a shaker. Figure 8 shows the wheel mounted on the structure. The motivation is to verify that we can accurately predict the response to an actual wheel which, with it's internal compliance and mass distribution, is a more complex mechanical device than a shaker. Figure 9 shows a comparison between the predicted response (in blue) with the measured response (in red) as a function of wheel speed. Notice that the prediction nicely over bounds the measurement by about a factor of two at most wheel speeds, lending confidence that our predictive capabilities and both accurate and conservative. Note also that the high levels of response (hundreds of nanometers) are due to the facts that (i) the wheel is much noisier than the ones intended for use on SIM, and (ii) the data was taken with the wheel in the hard mounted configuration.

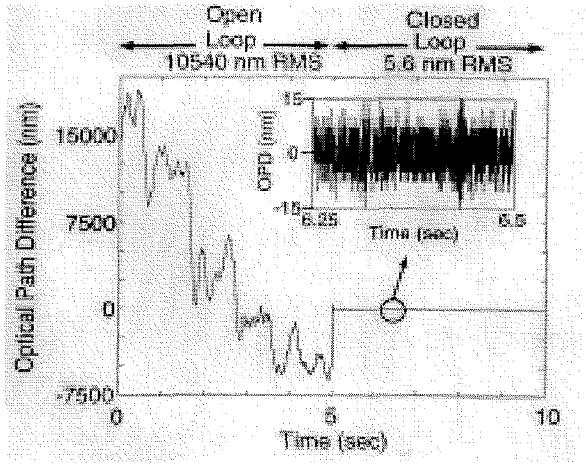

Figure 7 – Time Trace of STB-1 Fringe Tracking OPD with Control Loops Open/Closed

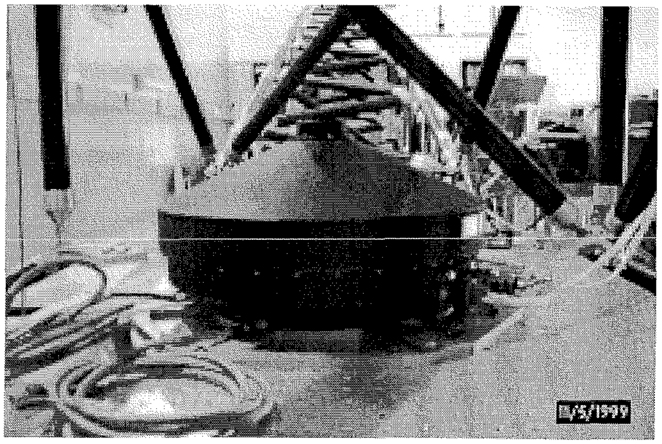

Figure 8 – Flight Spare Magellan Reaction Wheel Hard Mounted on STB-1

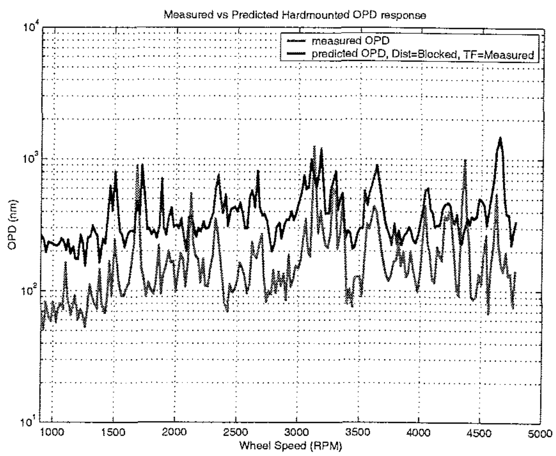

Figure 9 – Wheel Response, Predict vs Measurement

As the name implies, STB-3 is a three-baseline testbed. It's objectives are twofold: (1) to demonstrate that information from the guide interferometers and the metrology system can be fed at high bandwidth to the science interferometer enabling it to track, in angle and phase, dim science stars; (2) to demonstrate the capability to integrate and operate a system of comparable complexity to the flight instrument, thereby serving as a pathfinder for the flight system integration and test.

The STB-3 approach is to proceed in two phases. In Phase 1, we will develop dim star phase tracking on optical tables, which entails three-baseline "pathlength feedforward." Phase 2 moves the three interferometers onto a SIM-scale flexible structure and repeats the dim star tracking experiments, demonstrating rejection of disturbances at the levels required by SIM.

The testbed is currently conducting Phase 1 testing on optical tables (Figure 10). We are tracking fringes on all three interferometers and are stabilizing dim star fringes at near flight levels in the face of simulated spacecraft attitude motions of the table. Figures 11 and 12 show, respectively in the time and frequency domains, the level of attenuation achieved so far. The 65 dB rejection exceeds a factor of 1,000 and is accomplished at an attitude disturbance frequency of 0.1 Hz, which is over 10 times faster than the expected on orbit frequency of sub 0.01 Hz. If we succeed in quieting the laboratory environment somewhat, we hope to demonstrate still better performance closer to the flight disturbance frequency. Another factor of 10 improvement would more than meet flight requirements. By early 2002 we plan to relocate the optics to the 9-meter flexible structure shown in Figure 13 and begin vibration attenuation testing.

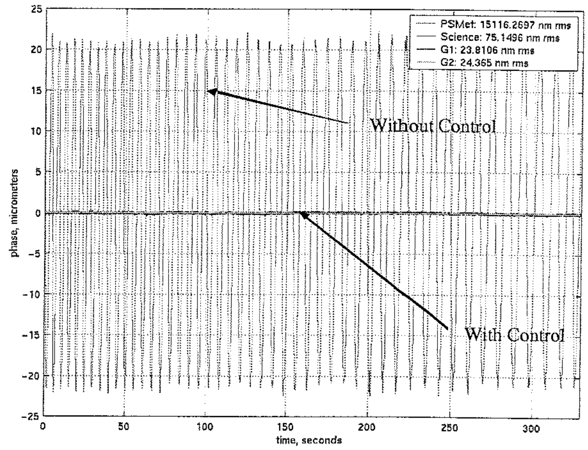

Figure 11 – Time Domain Dim Star Tracking Data

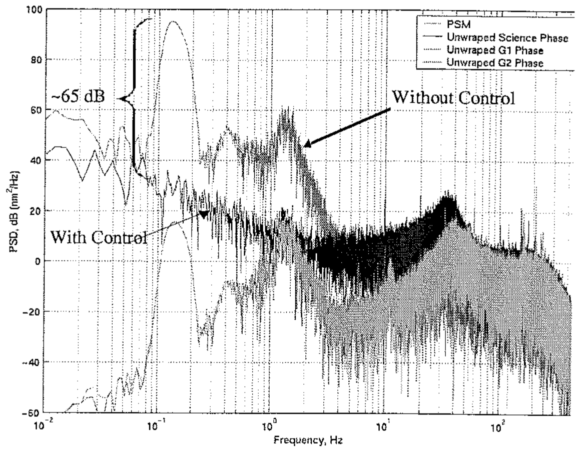

Figure 12 – Frequency Domain Dim Star Tracking Data

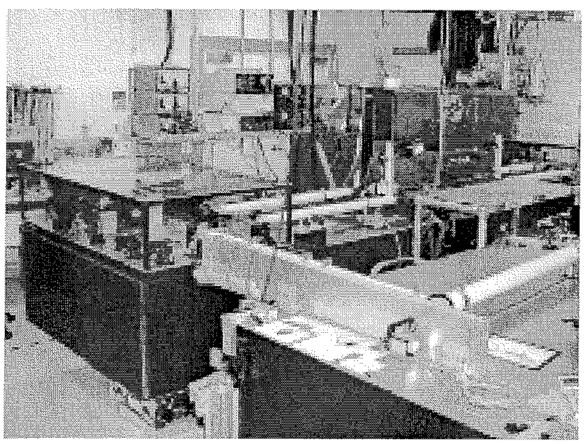

Figure 10 – STB-3 on Optical Tables

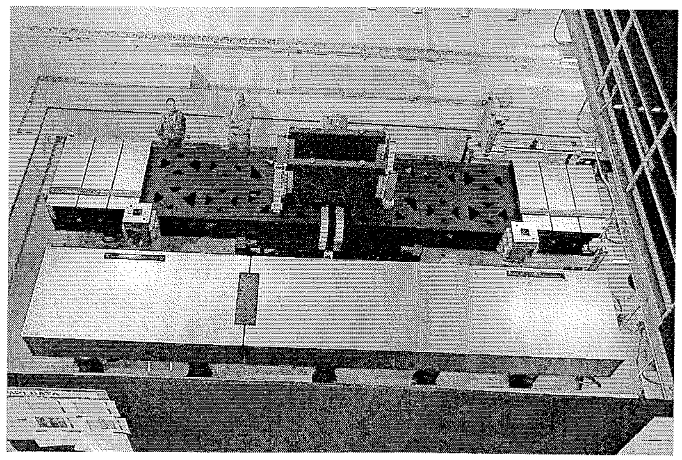

Figure 13 – STB-3 Structure (shown upper portion of photo) Installed in Laboratory High Bay

Microarcsecond Metrology (MAM) Testbed—The sub-nanometer and microarcsecond measurement technology needed by SIM will be demonstrated through a combination of component development and testbed demonstrations. MAM is a single baseline white light interferometer fed by a reverse interferometer pseudostar and is currently being built at JPL and Lockheed-Martin (see Figure 14).

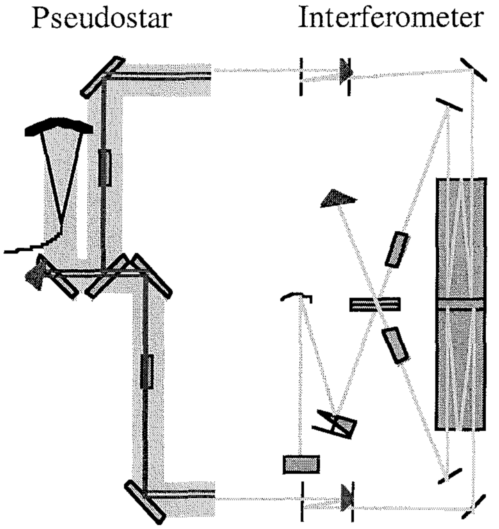

Figure 14 – Schematic of MAM Interferometer and Pseudostar

MAM's single interferometer includes siderostats for wide angle acquisition, fast steering mirrors for high precision pointing, a delay line to control optical path and a beam combiner with both pointing and pathlength sensors. Additionally, internal metrology beams integrated into the beam combiner are used to measure the optical path between the combiner and each arm of the interferometer. An inverse interferometer pseudostar (IIPS) is used to feed white light into the MAM interferometer (see photo in Figure 15). The IIPS also uses internal metrology beams that monitor the optical path from its main beamsplitter to the fiducials on the MAM interferometer. By comparing the white light fringe measurement and the metrology measurements from both the interferometer and the pseudostar as the angle of the "star" is varied, one can measure optical path measurement errors arising from a number of sources that are present on SIM. These include diffraction effects from moving delay lines, surface figure errors in the interferometer optics, and fringe estimation errors.

Both the MAM interferometer and IIPS are to be placed in a vibration-isolated, thermally stabilized vacuum chamber large enough to accommodate the 2-meter scale interferometric baselines. Doing so eliminates optical path errors due to fluctuations in the refractive index of air. The MAM experiment is currently partially operational and will be performing experiments throughout 2002 and 2003. To meet SIM's requirements, the MAM experiment will achieve its goal of 150-pm optical path measurement accuracy over a 1-degree field of regard.

In order for SIM and the MAM system testbed to be successful two critical component technologies must first be demonstrated. These are laser metrology with relative motion accuracies less than 50 pm and white light fringe sensors with less than 30 pm error.

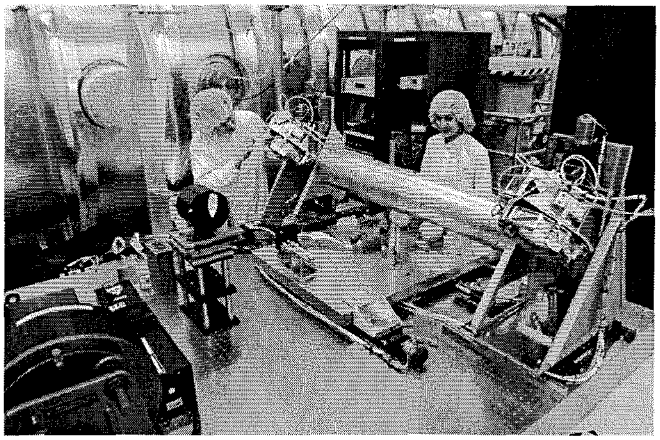

Figure 15 – MAM Inverse Interferometer Pseudostar (IIPS) in Final Assembly

A laser metrology gauge consists of a beam launcher interposed between two corner cubes whose relative motion is to be measured. The beam launcher has a detector capable of sensing minute changes in the phase of the laser beam that interrogates the two corner cubes. Figure 16 shows a photo of a prototype beam launcher. It is built mostly out of zerodur parts since thermal stability if very important. Test data indicates that we have succeeded in building a laser gauge with less than 100 pm of error over microns of

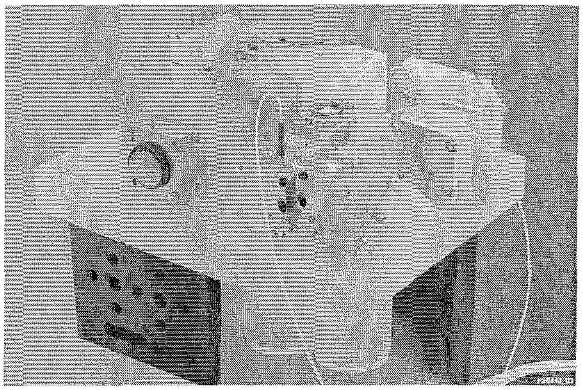

Figure 16 – Photo of Prototype Metrology Beam Launcher

corner cube motion (Figure 17) and with thermal stability of less than 8 nm/mK of bulk temperature change (Figure 18). Both of these performance parameters are within a factor of 2-4 of ultimate flight requirements indicating that the basic technology is essentially in hand.

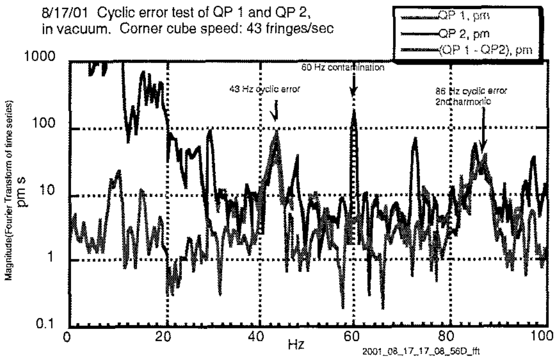

Figure 17 – Gauge Performance of Under 100 pm Over Micron Regime Corner Cube Excursions

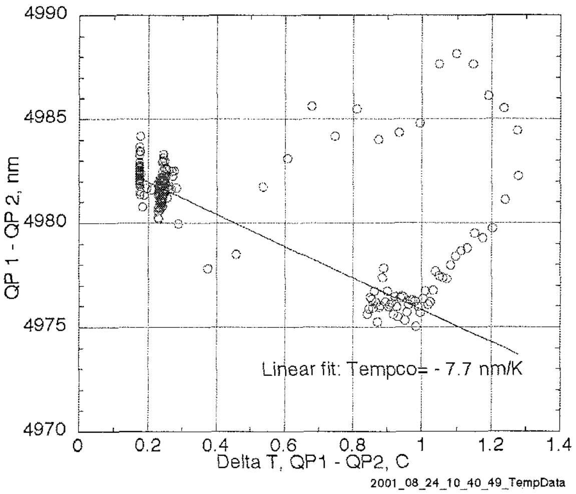

Figure 18 – Gauge Performance of Under 8 nm/mK Thermal Sensitivity to 1 Kelvin Class Temperature Excursion

The white light experiment has recently demonstrated the ability to measure broadband fringe positions to less than 30 pm.

Figure 19 shows a layout of the experiment that utilizes the beam combiner components of the MAM testbed. White light is fed into the beam combiner, propagates backward through the beam combiner and delay line and is retro-reflected by the fast steering mirror back to the fringe detector. Fringe estimates are made by monitoring the fringe intensity pattern while modulating the optical path approximately one wave using the PZT stage of the delay line. A He-Ne laser is simultaneously injected into the white light fiber and is used as a truth reference for the fringe position. Figure 20 shows an Allan Variance curve (bounded by 90% confidence error bar curves) of the difference between the phase estimate from the white light fringe detector and the He-Ne laser signal. At the 30 second integration time planned for SIM, fringe read error is about 22 pm, beating the flight requirement with margin. This is a huge step forward for the SIM technology development effort.

Subsystem Testbeds—In addition to the major system level testbeds, a number of testbeds are planned to focus more sharply on demonstrating particular capabilities better tested at lesser degrees of integration. The Thermal Opto-mechanical (TOM) Testbed is an example. TOM, under the direction of Lockheed-Martin's Palo Alto Advanced Technology Center, is aimed at exploring the response of optical figure to small changes in thermal conditions. This is a critical area for SIM. Since the SIM metrology system samples only a small portion of each collecting aperture, sub-nanometer changes to optical figure across the apertures during the course of an observation would result in misleading estimates of the optical path excursions seen by starlight. SIM's design solution is to maintain very tight (< 10 mK) thermal control of time varying gradients across the collecting optics. Thermal-optical-mechanical modeling indicates that these small mirror temperature excursions will insure acceptably small distortions in optical figure. The TOM Testbed's job is to prove that this is the case.

TOM will proceed in three major steps. Test #1 has been completed. This is a thermal-only experiment where a 33 cm Pyrex mirror (Figure 21) in a thermal vacuum tank is exposed to time varying thermal loads and its temperature response is recorded. These data are compared to predictive thermal models. Test #2 introduces optical figure measurement so that mirror temperature changes can be experimentally correlated with changes in figure. Test #2 uses a relatively high CTE test optic so that mechanical response will be exaggerated (compared to SIM) leading to high SNR measurements and easier model comparison. Test #3 introduces a flight-traceable low-CTE telescope as the test optic and a test environment closely emulating on-orbit conditions.

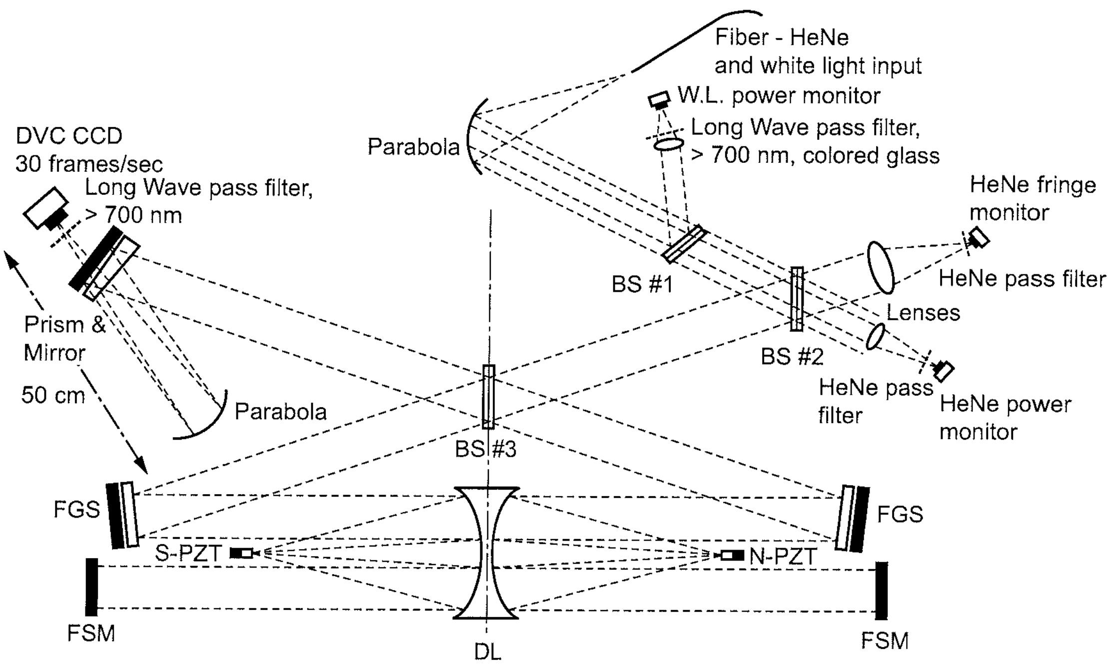

Figure 19 – Layout of White Light Fringe Detection Experiment

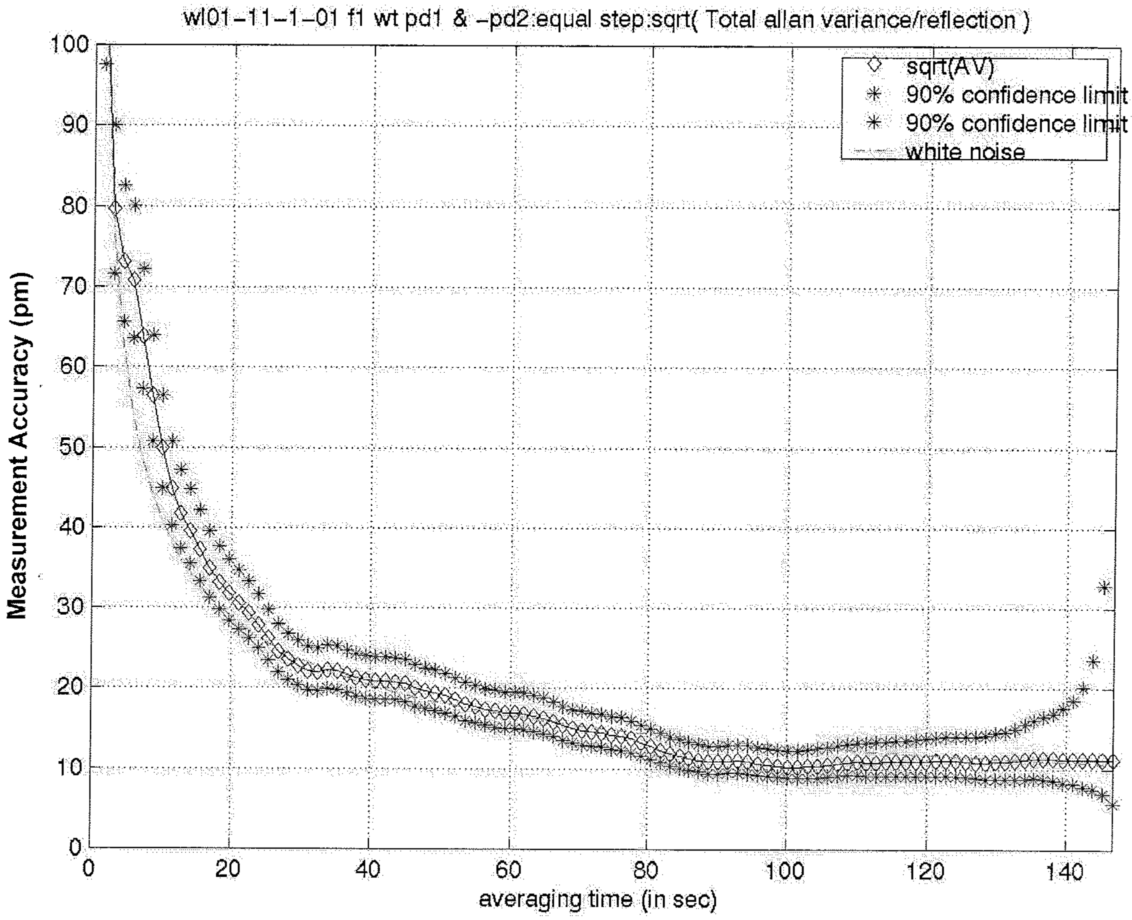

Figure 20 – Allan Variance of Consistency Between White Light Fringe Readout and HeNe Laser Gauge

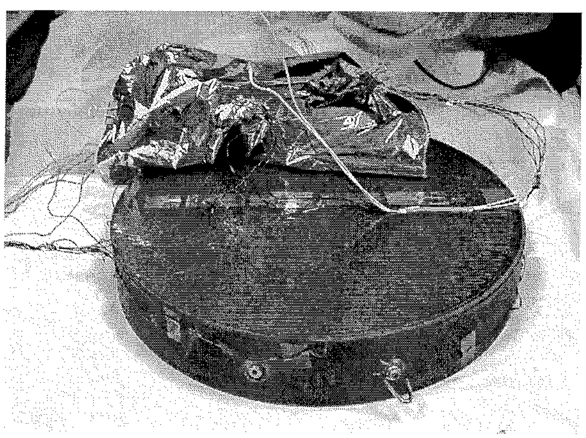

Figure 21 – Pyrex Mirror for TOM Test #1

Test #1 objectives were to verify temperature sensor performance and thermal modeling capability in the mK regime. Both objectives were met in impressive fashion. The temperature sensors, platinum resist thermometers (PRTs), were shown capable of sub mK resolution. The thermal modeling predicted temporal changes in through-mirror temperature gradients to an accuracy of about 20% (Figure 22). This is critical to SIM since it is the through-mirror gradients that are expected to produce the majority of mirror deformation. This postulate will be examined in Test #2.

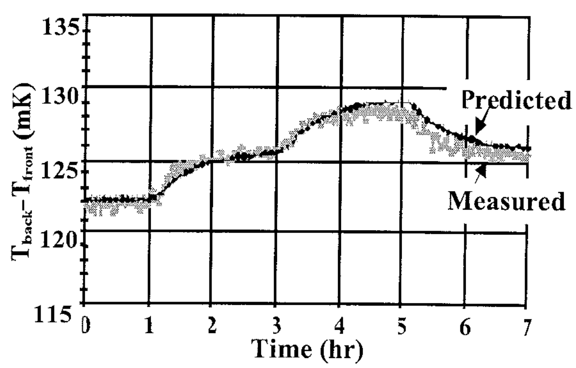

Figure 22 – Time Variation of TOM Mirror Front-to-Back Thermal Gradient—Actual vs Predict

Another subsystem testbed is aimed at demonstrating that the laser metrology gauges discussed above can be built up into multiple gauge configurations capable of measuring the relative motion of optical fiducials (viz., corner cubes) in more than one dimension. Such a multiple gauge configuration is referred to as an "optical truss." On SIM a three dimensional optical truss consisting of 13 gauges is used to monitor the relative motion of the corner cubes located on the system's main starlight receiving optics. The testbed that will demonstrate the optical truss concept is called Kite for reasons that become obvious when one looks at the configuration depicted in Figure 23. Kite consists of 6 laser gauges in a plane laid out to resemble a kite. The call outs in the figure are the passive corner cube (PCC), the active corner cube (ACC), two triple corner cubes (TCC) and 6 so-called "quick prototype" or QP beam launchers of the type pictured in Figure 16. The primary experiment is to move the ACC in x and y over about 10 microns and to measure that motion with the 6-gauge optical truss to about the 100 pm level. Six gauges in a plane is the smallest number of gauges that allow for a multi-dimensional consistency test. That is to say that using the outputs of any of five gauges is sufficient to predict the output of the sixth gauge. If these quantities agree to 100 pm, then the program will declare success on the optical truss technology and move toward a test of a three dimensional optical truss in conjunction with the build of the flight system.

Kite is currently procuring all the necessary components to build the testbed in the spring of 2002 and produce data by summer. One of the steps that has been taken to reduce the risk inherent in this aggressive schedule was to build a lower quality mock up of Kite. Pictured in Figure 24 the "interim Kite" is already operational. It's metrology gauges are older models that are incapable of making picometer level measurements. Nevertheless it provides an excellent venue for testing the software and electronics that will drive the final experiment once the new beam launchers are built.

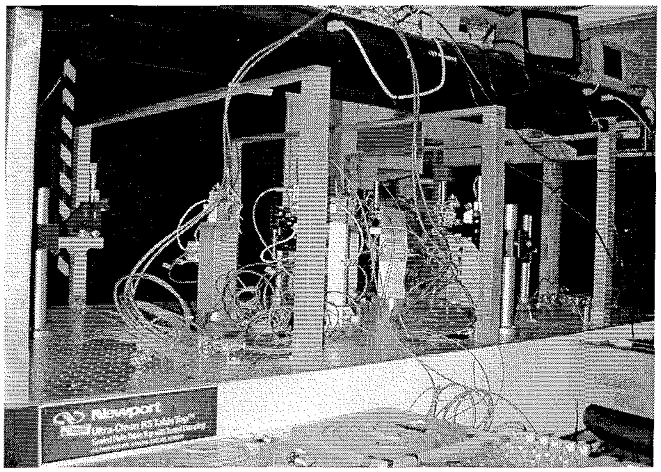

Figure 24 – Interim Kite

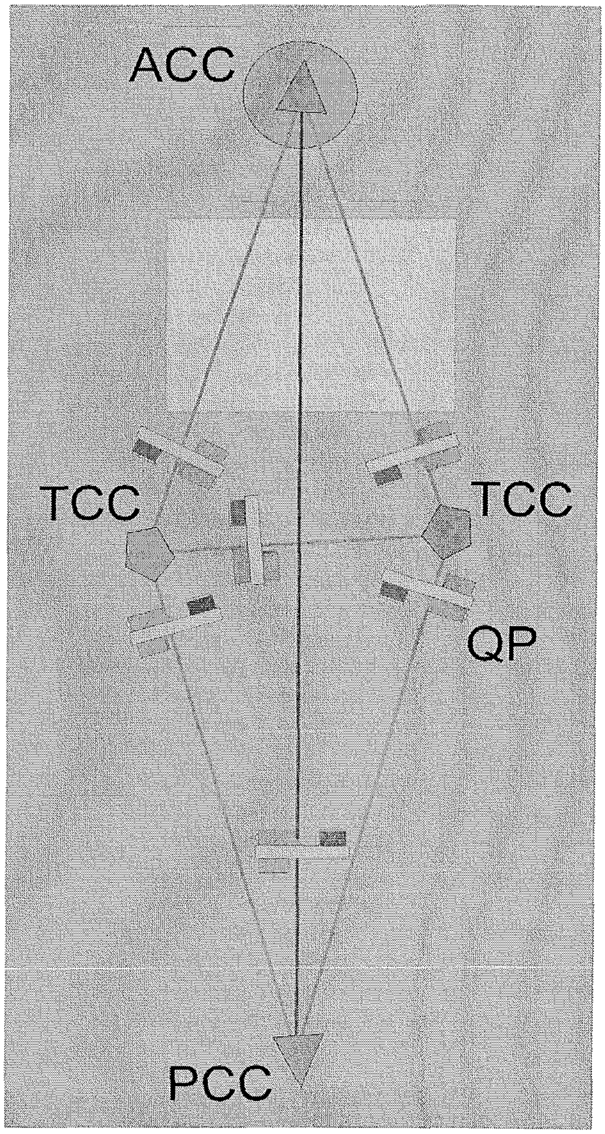

Figure 23 – Kite Layout

4. Summary

Scientifically, SIM will open new vistas, including the discovery of Earth mass planets in our galactic neighborhood. However, the technology necessary to make SIM a reality presents unprecedented challenges in the fields of nanometer stabilization, picometer sensing, and complex system integration, test, and autonomous operation. However, we are far from starting from scratch on this development effort. Work on these technologies—dispersed at first, now much more highly focussed—has been underway for almost 20 years. As exemplified by the sub 100 pm results on laser metrology gauges and "stellar" fringe sensors, the component technologies for SIM are essentially in hand. What remain outstanding are critical demonstrations at the subsystem and system level. With these completed by 2004 SIM will be ready to begin flight system development with its formidable technical risks well understood and its critical technology in hand.

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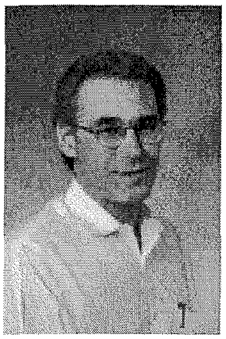

7. Biography

Robert Laskin—*is the Flight System Manager and Project Technologist for the Space Interferometry Mission (SIM). In this capacity he is responsible for developing the technology needed by SIM, seeing that it is properly inserted in the flight system, and keeping a watchful eye on the needs of future more ambitious space interferometers. Dr. Laskin received undergraduate degrees from Yale College (1974) and Columbia University (1978), a Masters from Stanford University in 1979, and the Ph.D. from Columbia in 1982, the latter three degrees all in mechanical engineering. Since graduating with his doctorate he has been with JPL, working largely on precision pointing, stabilization, and figure control of complex space optical systems. He joined JPL's Interferometry Technology Program in 1988 as system engineer and became program manager in 1991. He assumed his responsibilities as SIM Project Technologist in 1997 when SIM officially became a project and took on the additional title of Flight System Manager in early 2001.*