FINAL

The Space Interferometry Mission (SIM)—Revolutionary Astronomy, Breakthrough Technology

Robert A. Laskin
SIM Flight System Manager
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109-8099
818-354-5086
robert.a.laskin@jpl.nasa.gov
http://www.jpl.nasa.gov/sim

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

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.

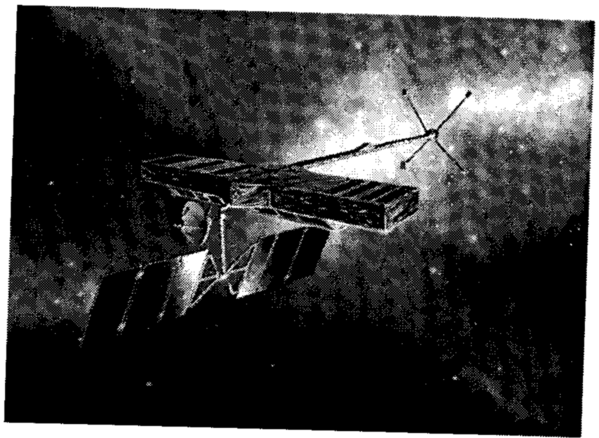

Figure 1 – Artist's Rendering of SIM

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 dopler 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 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.).

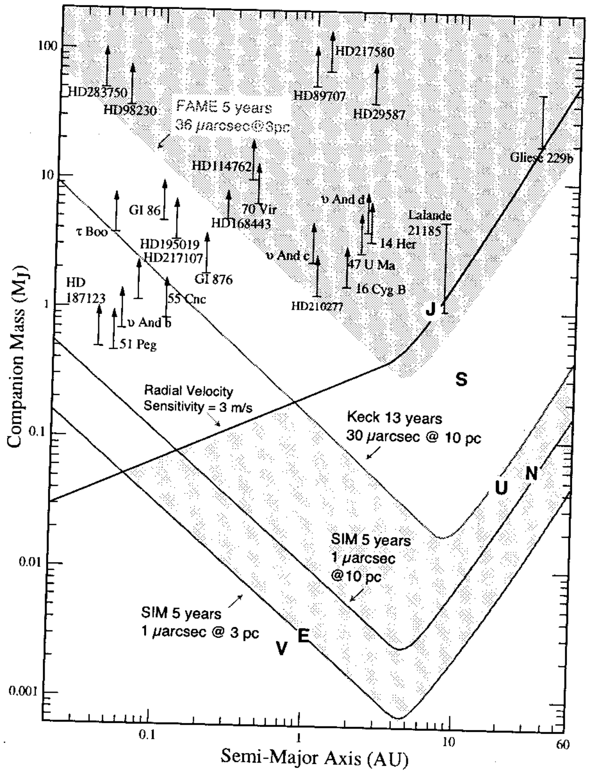

Figure 2 – SIM Extra Solar Planet Discovery Space

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.

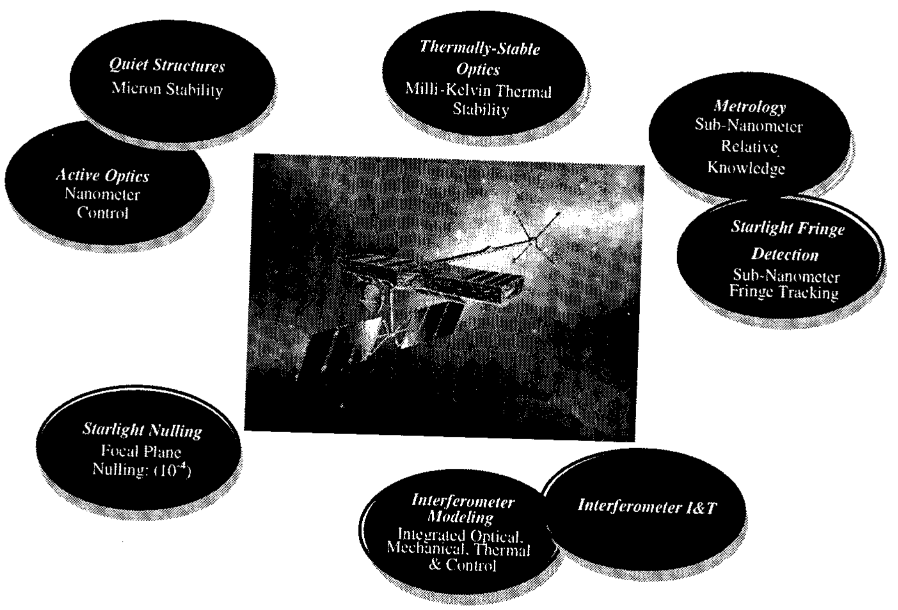

Figure 3 – Key Technologies for SIM

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.

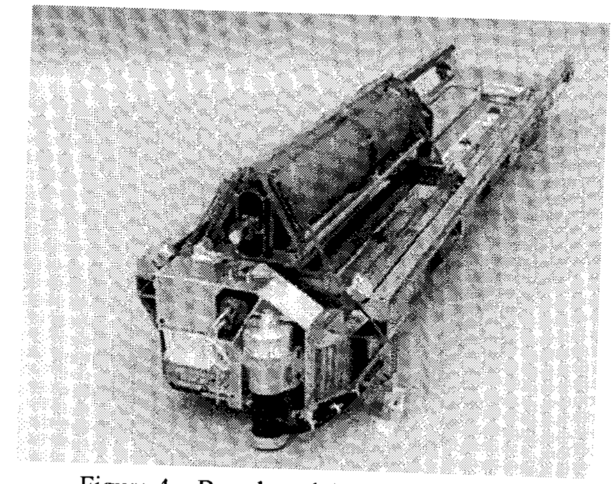

Figure 4 – Brassboard Optical Delay Line

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.

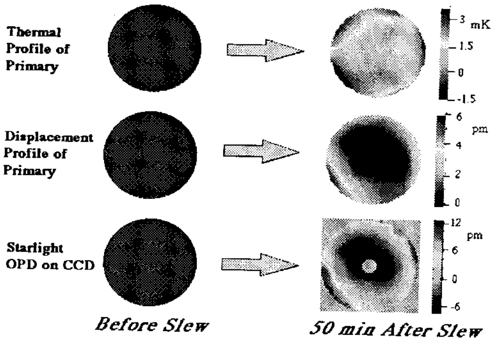

Figure 5 – Collector Deformation Map Over Temperature

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.

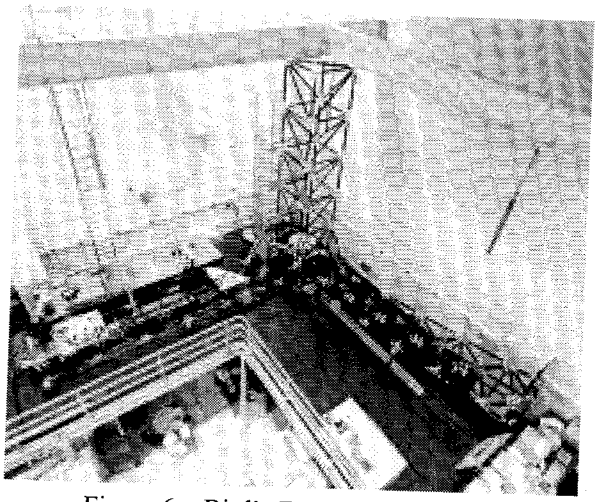

Figure 6 – Bird's Eye View of STB-1

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).

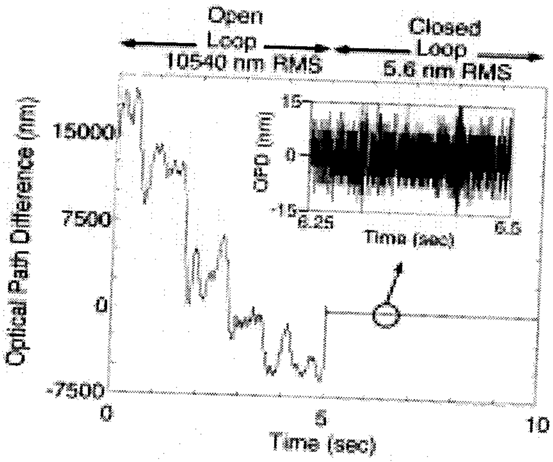

Figure 7 – Time Trace of STB-1 Fringe Tracking OPD with Control Loops Open/Closed

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 8). 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. By early 2002 we plan to relocate the optics to a 9-meter flexible structure and begin vibration attenuation testing.

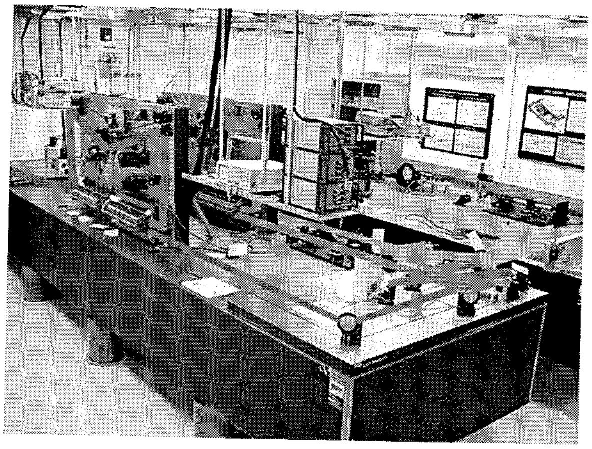

Figure 8 – STB-3 on Optical Tables

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 9).

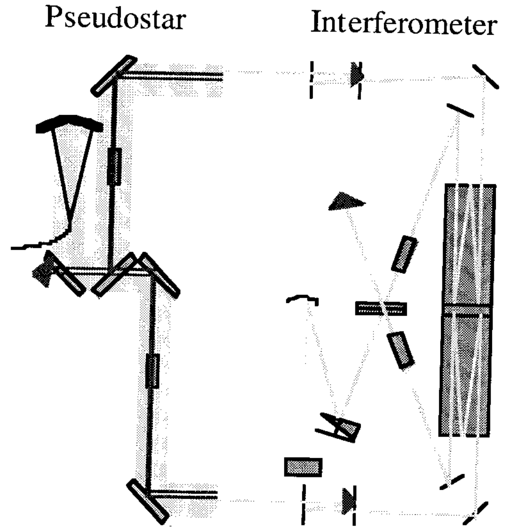

Figure 9 – Schematic of MAM Interferometer and Pseudostar

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. 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.

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 10 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

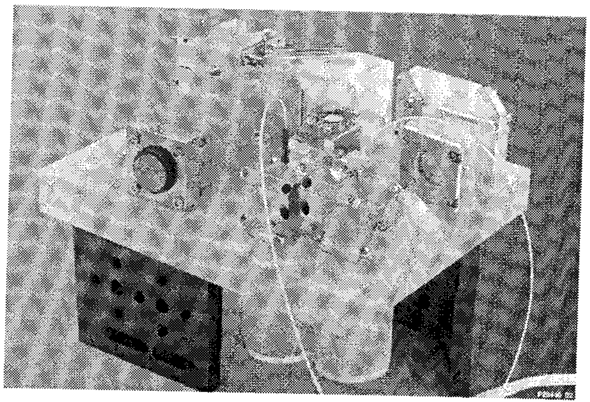

Figure 10 – Photo of Prototype Metrology Beam Launcher

corner cube motion (Figure 11) and with thermal stability of less than 8 nm/mK of bulk temperature change (Figure 12). 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.

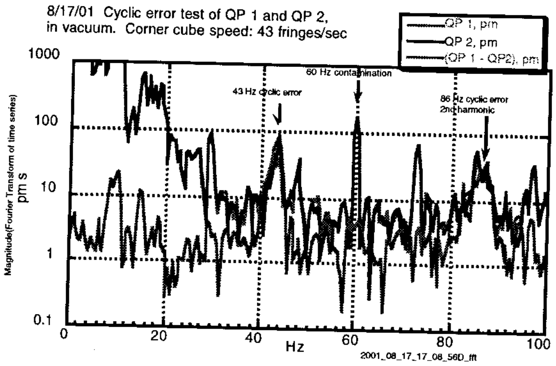

Figure 11 – Gauge Performance of Under 100 pm Over Micron Regime Corner Cube Excursions

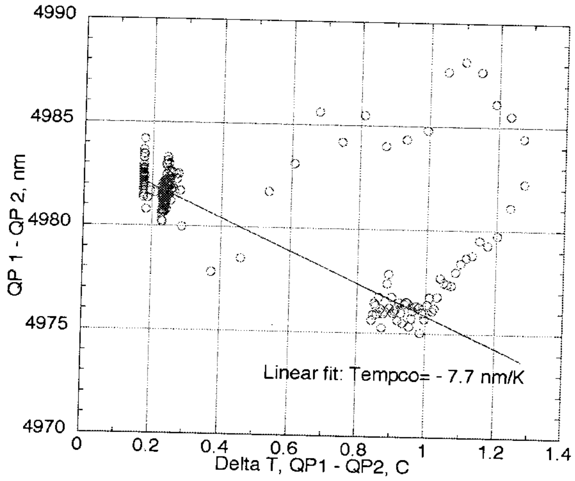

Figure 12 – Gauge Performance of Under 8 nm/mK Thermal Sensitivity to 1 Kelvin Class Temperature Excursion

The white light experiment will demonstrate the ability to measure broadband fringe positions to less than 30 pm.

Figure 13 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 14 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 80 pm, within a factor of three of the goal. Notice that at longer integration times the 30 pm requirement is surpassed, indicating that we may eventually have to face a tradeoff between integration time and astrometric precision.

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 15) 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.

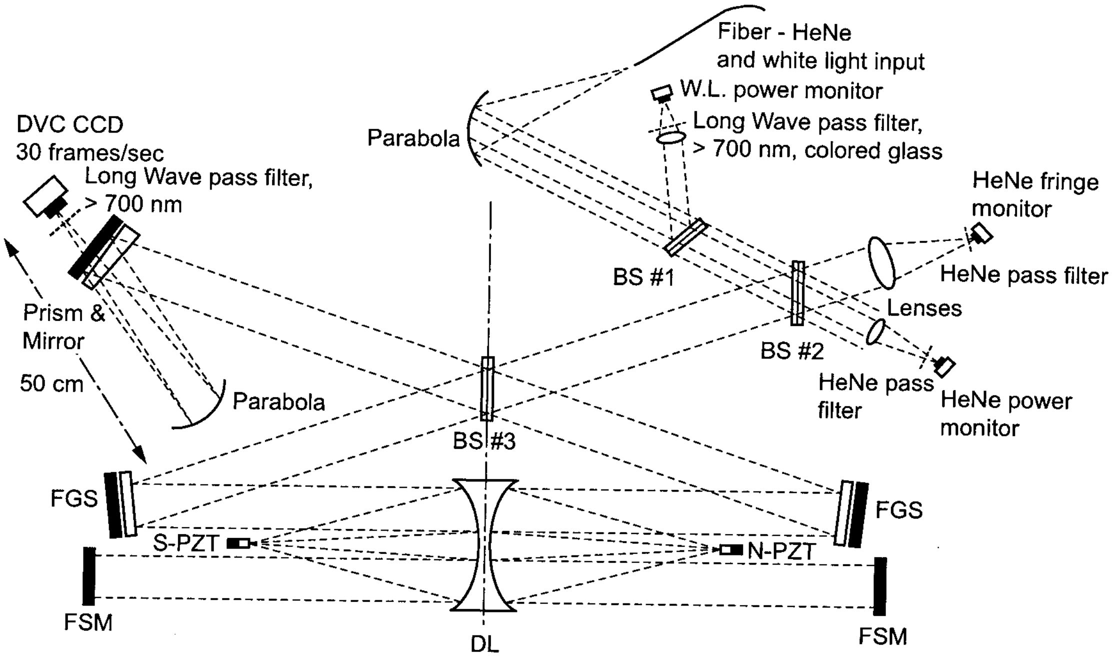

Figure 13 – Layout of White Light Fringe Detection Experiment

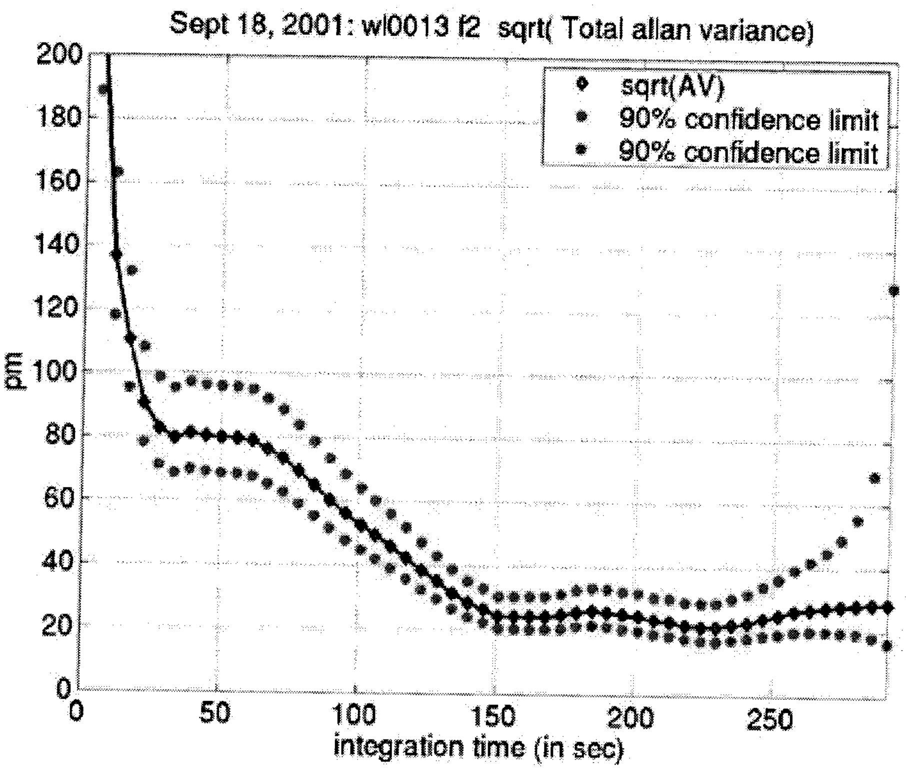

Figure 14 – Allan Variance of Consistency Between White Light Fringe Readout and HeNe Laser Gauge

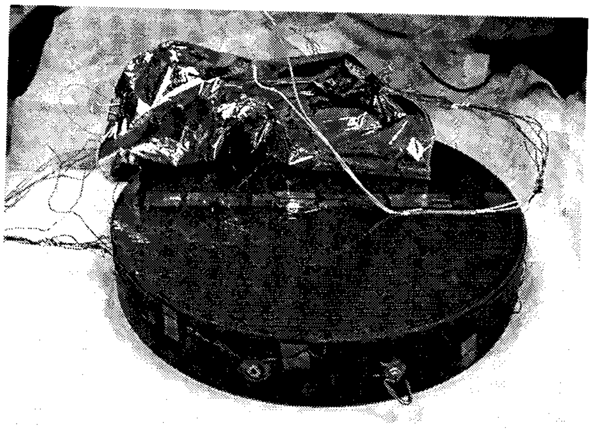

Figure 15 – Pyrex Mirror for TOM Test #1

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 16). 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.

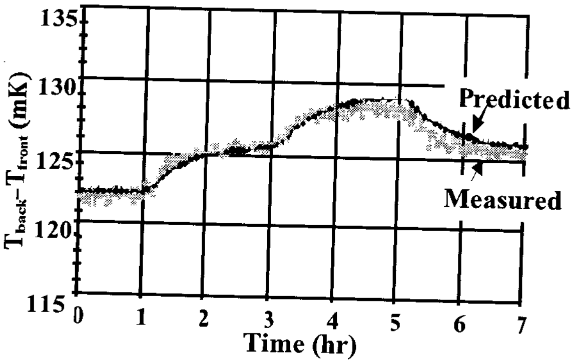

Figure 16 – Time Variation of TOM Mirror Front-to-Back Thermal Gradient—Actual vs Predict

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.

5. ACKNOWLEDGMENTS

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. The author wishes to thank Judith Dedmon for help in preparing this paper. Thanks are also due to the entire JPL, Lockheed-Martin, and TRW team whose outstanding work is reported in this paper.

6. REFERENCES

[1] R. A. Laskin, A. M. San Martin, "Control/ Structure System Design of a Spaceborne Optical Interferometer," AAS/AIAA Astrodynamics Specialist Conference, August 1989.

[2] S. W. Sirlin, R. A. Laskin, "*Sizing of Active Piezoelectric Struts for Vibration Suppression on a Space-Based Interferometer*," Joint U.S./Japan Conference on Adaptive Structures, November 1990.

[3] D. Eldred and M. O'Neal, "*The Phase B Testbed Facility*," Proceedings of the ADPA Active Materials and Adaptive Structures Conference, Alexandria, VA, November 1991.

[4] D. Eldred and M. O'Neal, "*The JPL Phase B Interferometer Testbed*," Proceedings of 5th NASA/ DoD Control Structure Interaction Technology Conference, South Lake Tahoe, Mar 1992.

[5] E. Anderson, M. Trudent, J. Fanson, and P. Pauls, "*Testing and Application of a Viscous Passive Damper for use in Precision Truss Structures*," Proceedings of 32nd AIAA SDM Conf., pp. 2795–2807, 1991.

[6] J. Fanson, G. Blackwood, and C. Chu, "*Experimental Evaluation of Active-Member Control of Precision Structures*," Proceedings NASA/DOD Controls-Structure Interaction Technology 1989, NASA Conference Publication 3041, Jan 29–Feb 2, 1989.

[7] J. Fanson, G. Blackwood, and C. Chu, "*Active/ Member Control of Precision Structures*," Proceedings of the 30th AIAA Structures, Structural Dynamics and Materials Conference, Mobile, AL, April 1989.

[8] B. Wada and E. Crawley, "Adaptive Structures," *Journal of Intelligent Material Systems and Structures*, Vol. 1, No. 2, pp. 157–174, 1990.

[9] J. Fanson, E. Anderson, and D. Rapp, "Active Structures for Use in Precision Control of Large Optical Systems," *Optical Engineering*, Vol. 29, No. 11, ISSN 0091-3286, pp. 1320–1327, Nov. 1990.

[10] E. Anderson, D. Moore, J. Fanson, and M. Ealey, "Development of an Active Truss Element for Control of Precision Structures," *Optical Engineering*, Vol. 29, No. 11, ISSN 0091-3286, pp. 1333–1341, Nov. 1990.

[11] C. Chu, B. Lurie, and J. O'Brien, "*System Identification and Structural Control on the JPL Phase B Testbed*," Proceedings of 5th NASA/DoD Control Structure Interaction Technology Conference, South Lake Tahoe, March 1992.

[12] B. Lurie, J. O'Brien, S. Sirlin, and J. Fanson, "*The Dial-a-Strut Controller for Structural Damping*," ADPA/ AIAA/ASME/SPIE Conf. on Active Materials and Adaptive Structures, Alexandria VA, Nov. 5–7, 1991.

[13] M. Milman and C. C. Chu, "Optimization methods for passive damper placement and tuning," *J. Guidance, Control, and Dynamics*, to appear.

[14] C. C. Chu and M. Milman, "Eigenvalue error analysis of viscously damped structures using a Ritz reduction method," *AIAA J.*, 30, 1992.

[15] J. Fanson and M. Ealey, "Articulating Fold Mirror for the Wide Field/Planetary Camera-2," Active and Adaptive Optical Components and Systems-2, *SPIE*, Vol. 1920, Albuquerque, 1993.

[16] J. Spanos, Z. Rahman and A. von Flotow, "Active Vibration Isolation on an Experimental Flexible Structure," Smart Structures and Intelligent Systems, *SPIE*, 1917-60, Albuquerque, NM, 1993.

[17] J. Spanos and M. O'Neal, "*Nanometer Level Optical Control on the JPL Phase B Testbed*," ADPA/AIAA/ ASME/SPIE Conf. on Active Materials and Adaptive Structures, Alexandria VA, Nov. 5–7, 1991.

[18] J. Spanos and Z. Rahman, "*Optical Pathlength Control on the JPL Phase B Testbed*," Proceedings of 5th NASA/DoD Control Structure Interaction Technology Conference, South Lake Tahoe, March 1992.

[19] J. T. Spanos, Z. Rahman, C. Chu and J. O'Brien, "*Control Structure Interaction in Long Baseline Space Interferometers*," 12th IFAC Symposium on Automatic Control in Aerospace, Ottobrunn, Germany, Sept. 7–11, 1992.

[20] D. Redding and W. Breckenridge, "Optical modeling for dynamics and control analysis," *J. Guidance, Control, and Dynamics*, 14, 1991.

[21] D. Redding, B. M. Levine, J. W. Yu, and J. K. Wallace, "*A hybrid ray trace and diffraction propagation code for analysis of optical systems*," SPIE OELAse Conf., Los Angeles, CA, 1992.

[22] H. C. Briggs, "*Integrated modeling and design of advanced optical systems*," 1992 Aerospace Design Conf., Irvine, CA, 1992.

[23] M. Milman, M. Salama, R. Scheid, and J. S. Gibson, "Combined control-structural optimization," *Computational Mechanics*, 8, 1991.

[24] M. Milman, M. Salama, M. Wette, and C. C. Chu, "*Design optimization of the JPL Phase B testbed*," 5th NASA/DoD Controls-Structures Interaction Technology Conf., Lake Tahoe, NV, 1992.

[25] M. Milman and L. Needels, "*Modeling and optimization of a segmented reflector telescope*," SPIE Conf. on Smart Structures and Intelligent Materials, Albuquerque, NM, 1993.

[26] L. Needels, B. Levine, and M. Milman, "*Limits on Adaptive Optics Systems for Lightweight Space Telescopes*," SPIE Conf. on Smart Structures and Intelligent Materials, Albuquerque, NM, 1993.

[27] G. W. Neat, L. F. Sword, B. E. Hines, and R. J. Calvet, "*Micro-Precision Interferometer Testbed: End-to-End System Integration of Control Structure Interaction Technologies*," Proceedings of the SPIE Symposium on OE/Aerospace, Science and Sensing, Conference on Spaceborne Interferometry, Orlando, FL, 1993.

[28] L. F. Sword and T. G. Carne, "Design and Fabrication of Precision Truss Structures: Application to the Micro-Precision Interferometer Testbed," Proceedings of the SPIE Symposium on OE/Aerospace, Science and Sensing, Conference on Spaceborne Interferometry, Orlando, FL, 1993.

[29] B.E. Hines, "*Optical Design Issues for the MPI Testbed for Space-Based Interferometry*," Proceedings of the SPIE Symposium on OE/Aerospace, Science and Sensing, Conference on Spaceborne Interferometry, Orlando, FL, 1993.

[30] M. Shao, M. M. Colavita, B. E. Hines, D. H. Staelin, D. J. Hutter, K. J. Johnson, D. Mozurkewich, R. S. Simon, J. L. Hersey, J. A. Hughes, and G. H. Kaplan, "Mark III Stellar Interferometer," *Astron. Astrophysics* 193, pp. 357–371, 1988.

[31] G. Neat, R. Laskin, J. Regner, and A. von Flotow, "*Advanced Isolation/Precision Pointing Platform Testbed for Future Spacecraft Missions*,"

17th AAS Guidance and Control Conference, Keystone, CO, Feb. 1994.

[32] H. Gutierrez, Marie Levine, and R. Grogan "*Analysis of IPEX-II Pre-Flight Ground Integration Test Data*," Report JPL D-14905, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, September 1998 (internal document).

[33] M. M. Colavita, J. K. Wallace, B. E. Hines, U. Gursel, F. Malbet, D. L. Palmer, X. P. Pan, M. Shao, J. W. Yu, A. F. Boden, P. J. Dumont, J. Gubler, D. C. Koresko, S. R. Kulkarni, B. F. Lane, D. W. Mobley, G. T. van Belle, "The Palomar Testbed Interferometer," *ApJ* 510, 1999 (in press).

[34] M. Levine, "*The Interferometry Technology Program Flight Experiments: IPEX I & II*," Proc. of SPIE Astronomical Telescopes and Instrumentation Conference, Kona, HI, March 1998.

[35] M. Levine, R. Bruno and H. Gutierrez, "*Interferometry Program Flight Experiment #1: Objectives and Results*," Proc. of 15th International Modal Analysis Conference, Santa Barbara, CA, Feb. 1998.

[36] G. Blackwood, "*The New Millennium Deep Space 3 Separated Spacecraft Interferometer Mission*," SPIE International Symposium on Astronomical Telescopes and Instrumentation, Paper no. 3350-83, March 1998.

[37] G. W. Neat, A. Abramovici, J. W. Melody, R. J. Calvet, N. M. Nerheim, J. F. O'Brien, "*Control Technology readiness for Spaceborne Optical Interferometer Missions*," The Space Microdynamics and Accurate Control Symposium, Toulouse, France, May 1997.

[38] C. Bell, J. Walker, and A. Lee, "*Interferometer Real Time Control for the Space Interferometry Mission*," AIAA/ IEEE 17th Digital Avionics Systems Conference held 31 October–6 November 1998 in Seattle, WA.

[39] R. J. Calvet, Jet Propulsion Lab.; B. Joffe, ITT Communications; D. M. Moore, R. L. Grogan, G. H. Blackwood, Jet Propulsion Lab, "*Enabling design concepts for a flight-qualifiable optical delay line*".

[40] "*Program for Analysis of a Complex Opto-Mechanical System*," NASA Tech Brief, Vol. 22, No. 2, Item #171.

[41] C. Papadimitriou, M. Levine and M. Milman, "*Application of a Finite Element Model Updating Methodology on the IPEX-II Structure*," Proc. of 15th International Modal Analysis Conference (IMAC), Santa Barbara, CA, Feb. 1998.

[42] C. Papadimitriou, M. Levine and M. Milman, "*Structural Damage Detection Using Modal Test Data*," International Workshop on Structural Health Monitoring, Stanford University, Sept. 18–20, 1997.

[43] C.-Y. Peng, M. Levine, and W. Tsuha, "*Interferometry Program Experiment IPEX-II Pre-Flight Ground Modal Test and Model Correlation Report*," Report JPL D-14809, Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, Sept. 1997 (internal document).

[44] C. Papadimitriou, M. Levine, and M. Milman, "A Methodology For Finite Element Model Updating Using Modal Data," 15th VPI Symposium on Structural Dynamics and Control, Blacksburg Virginia, June 1997.

[45] M. Levine and M. Milman, "*Experimental Verification of Integrated Opto-Structural Model Predictions*," SMACS (Space Microdynamics and Control) Conference, Toulouse, France, May 1997.

[46] M. Milman and M. Levine, "*Integrated Modeling Tools for Precision Multidisciplinary Systems*," SMACS (Space Microdynamics and Control) Conference, Toulouse, France, May 1997.

[47] M. B. Levine, M. H. Milman, and A. Kissil, "Mode Shape Expansion Techniques for Prediction: Experimental Evaluation," *AIAA Journal*, Vol. 34, No. 4, April 1996.

[48] Y. Gursel, "*Laser metrology gauges for OSI*," Proceedings of SPIE conference on Spaceborne Interferometry, Vol. 1947, pp. 188–197, 1993.

[49] Y. Gursel, "*Metrology for spatial interferometry*," Proceedings of SPIE conference on Amplitude and Intensity Spatial Interferometry, Vol. 2200, pp. 27–34, 1994.

[50] Y. Gursel, "*Metrology for spatial interferometry II*," Proceedings of SPIE conference on Spaceborne Interferometry II, Vol. 2477, p. 240–258, 1995.

[51] Y. Gursel, "*Metrology for spatial interferometry III*," Proceedings of SPIE conference on Space Telescopes and Instruments IV, Vol. 2807, pp. 148–161, 1996.

[52] Y. Gursel, "*Metrology for spatial interferometry IV*," Proceedings of SPIE conference on Small Spacecraft, Space Environments, and Instrumentation Technologies, Vol. 3116, pp. 12–26, 1997.

[53] Y. Gursel, "*Metrology for spatial interferometry V*," Proceedings of SPIE conference on Astronomical Interferometry, Vol. 3350, pp. 571–587, 1998.

[54] S. S. Joshi, J. W. Melody, and G. W. Neat, "*A Case Study on the Role of Structural/Optical Model*

Fidelity in Performance Prediction of Complex Opto-Mechanical Instruments," IEEE Conference on Decision and Control San Diego, CA, December 1997.

[55] S. S. Joshi, J. W. Melody, G. W. Neat, and A. Kissil, "*Benefits of Model Updating: A Case Study Using the Micro-Precision Interferometer Testbed,*" Proceedings of DETC'97 1997 ASME Design Engineering Technical Conference, Sacramento, CA, September 14–17, 1997.

[56] S. S. Joshi, M. Milman, and J. W. Melody, "*Optimal Passive Damper Placement Methodology for Interferometers Using Integrated Structures/Optics Modeling,*" AIAA Guidance, Navigation, and Controls Conference, New Orleans, LA, August 1997.

[57] J. Davis, W. J. Tango, A. J. Booth, T. A. ten Brummelaar, R. A. Minard and S. M. Owens, "*The Sydney University Stellar Interferometer I: The Instrument,*" Accepted by Monthly Notices of the Royal Astronomical Society.

[58] S. Shaklan, S. Azevedo, R. Bartos, A. Carlson, Y. Gursel, P. Halverson, A. Kuhnert, Y. Lin, R. Savedra, and E. Schmidtlin, *"The micro-arcsecond metrology testbed (MAM),"* Proceedings of SPIE conference on Astronomical Interferometry, Vol. 3350, pp. 571–587, 1998.

[59] A. Kuhnert, S. Shaklan, Y. Gursel, S. Azevedo, and Y. Lin, "*Metrology for the micro-arcsecond metrology testbed,*" Proceedings of SPIE conference on Astronomical Interferometry, Vol. 3350, pp. 571–587, 1998.

[60] S. Dubovitsky, D. Seidel, D. Liu, and R. Gutierrez, "*Metrology source for high-resolution heterodyne interferometer laser gauges,*" Proceedings of SPIE conference on Astronomical Interferometry, Vol. 3350, pp. 571–587, 1998.

[61] A. Carlson, S. Shaklan, R. Bartos, and S. Azevedo, "*Opto/mechanical design of the micro-arcsecond metrology testbed interferometer,*" Proceedings of SPIE conference on Astronomical Interferometry, Vol. 3350, pp. 571–587, 1998.

[62] E. Schmidtlin, S. Shaklan, and A. Carlson, "*Novel wide field-of-view retroreflector for the Space Interferometry Mission,*" Proceedings of SPIE conference on Astronomical Interferometry, Vol. 3350, pp. 571–587, 1998.

[63] S. Loiseau, S. Shaklan, D. Redding and E. Schmidtlin, "*Retroreflector diffraction modeling*".

[64] M. M. Colavita, A. F. Boden, S. L. Crawford, A. B. Meinel, M. Shao, P. N. Swanson, G. T. van Belle, G. Vasisht, J. M. Walker, J. K. Wallace, P. L. Wizinowich, "*Keck Interferometer,*" Proc. SPIE 3350, 776–784, 1998.

[65] A. F. Boden, C. D. Koresko, G. T. van Belle, M. M. Colavita, P. J. Dumont, J. Gubler, S. R. Kulkarni, B. F. Lane, D. Mobley, M. Shao, and J. K. Wallace, "The Visual Orbit of Iota Pegasi," *ApJ*, 1998 (in press).

[66] M. M. Colavita, "Fringe Visibility Estimators for the Palomar Testbed Interferometer," *PASP*, 1999 (in press).

[67] G. T. van Belle, B. F. Lane, R. R. Thompson, A. F. Boden, M. M. Colavita, P. J. Dumont, D. W. Mobley, D. Palmer, M. Shao, G. X. Vasisht, J. K. Wallace, M. J. Creech-Eakman, C. D. Koresko, S. R. Kulkarni, X. P. Pan, J. Gubler, "Radii and Effective Temperatures for G, K and M Giants and Supergiants," *AJ*, 1999 (in press).

[68] C. D. Koresko, G. T. van Belle, A. F. Boden, M. M. Colavita, M. J. Creech-Eakman, P. J. Dumont, J. Gubler, S. R. Kulkarni, B. F. Lane, D. W. Mobley, X. P. Pan, M. Shao, and J. K. Wallace, "The Visual Orbit of the 0.002" RS CVn Binary Star TZ Triangulum from Near-Infrared Long-Baseline Interferometry," *ApJL*, 1998 (in press).

[69] F. Malbet, J.-P. Berger, M. M. Colavita, M. Shao, J. K. Wallace, A. F. Boden, G. T. van Belle, D. W. Mobley, C. Beichman, C. D. Koresko, S. R. Kulkarni, B. F. Lane, and X. P. Pan, "A Protoplanetary disk around FU Orionis Resolved by Infrared Long-Baseline Interferometry," *ApJL*, 1998 (in press).

[70] A. F. Boden, G. T. van Belle, M. M. Colavita, P. J. Dumont, J. Gubler, C. D. Koresko, S. R. Kulkarni, B. F. Lane, D. W. Mobley, M. Shao, and J.K. Wallace, "An Interferometric Search for Bright Companions to 51 Pegasi," *ApJL*, 504 L39, 1998.

[71] R. L. Grogan, G. H. Blackwood, and R. J. Calvet, "*Optical Delay Line Nanometer Level Pathlength Control Law Design For Space-Based Interferometry,*" Proceedings of the 1998 SPIE International Symposium on Astronomical Telescopes and Instrumentation Astronomical Interferometry, April 1998.

[72] R. L. Grogan, R. Laskin, "*On Multidisciplinary Modeling of the Space Interferometry Mission,*" Proceedings of the 1998 American Controls Conference, June 1998.

[73] R. J. Calvet, B. Joffe, D. Moore, R. L. Grogan, and G. H. Blackwood, "*Enabling Design Concepts for a Flight-Qualifiable Optical Delay Line,*" Proceedings of the 1998 SPIE International Symposium on Astronomical Telescopes and Instrumentation Astronomical Interferometry, April 1998.