Technology for space optical and infrared interferometry

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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 Interferometry Technology Program at NASA's Jet Propulsion Laboratory is addressing these challenges with a development program that plans to establish technology readiness for the Space Interferometry Mission by early in the year 2001.

Keywords: interferometer, laser metrology, active control, vibration attenuation, integrated modeling

1. INTRODUCTION

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. Interferometry is the only known method to significantly improve (by orders of magnitude) the angular resolution of current astronomical telescopes and thereby meet several key scientific goals of the 21st century: measurement of stellar diameters, resolution of close binaries, detection, imaging, and spectroscopy of extra-solar planets, and the precise measurement of galactic and cosmic distance scales. 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. The Space Interferometry Mission (SIM) 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.

It is not surprising that such a huge step forward in observational power requires a concommitant 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.

The major scientific objectives of the Space Interferometry Mission are:
(a) Search for other planetary systems
(b) Calibration of distances and ages in the universe
(c) Study of dynamics and evolution of stars and star clusters in our galaxy
(d) Study of dynamics and evolution of active galactic nuclei
(e) Study of the structure of circumstellar disks

SIM will be an optical interferometer operating in Earth escape orbit where the benign thermal evironment is expected to ease the challenge of maintaining extremely high dimensional stability of its optical components. The artist's rendering of SIM (**Figure 1**) shows an instrument consisting of four operational two aperture interferometers over a baseline of approximately 10 meters. The collecting apertures are a modest 33 cm in diameter. The instrument operates in the visible waveband between 0.5 and 1.0 microns. In order to accomplish its scientific goals it will make wide angle astrometric measurements with a precision of 4 uas, narrow angle astrometric measurements with a precision of at least 1 uas, and will also perform synthesis aperture imaging (10 mas resolution) and starlight nulling at the factor of 10,000 extinction level. In most of its operating modes SIM uses two of interferometers as "guides" and a third for observing a science target. The forth interferometer serves as a back-up in case of a failure of one of the other three.

The Terrestrial Planet Finder (TPF), as its name suggests, will search for Earth-like planets in other solar systems and return "family portrait" images of these solar systems at the one pixel per planet resolution level. It will also have the capability of performing spectroscopy within its 7 - 17 micron operating waveband, enabling some level of characterization of atmospheric constituents of the planets it observes. TPF is envisioned as requiring a 100 meter interferometric baseline and apertures anywhere between 1.5 and 4 meters, depending upon its orbit relative to the Sun (a 1 AU orbit would require larger apertures than would, say, a 5 AU orbit due to the higher density of our own solar system's zodiacal cloud closer to the Sun). This tradeoff between aperture size and orbit is one of two key trades that must be made as TPF is defined over the next few years. The other key trade will decide whether to configure the system on a single large structure or as a constellation of separate spacecraft (both concepts are illustrated in **Figure 2**).

Given that SIM is the nearer term mission, the Interferometry Technology Program (ITP) at JPL is concentrating most of its current effort on providing technology readiness for SIM. And this paper will devote itself primarily to a discussion of SIM's technology needs and ITP's response to those needs. TPF, of course, will be a great beneficiary of the SIM technology development and it is anticipated that once the technology for SIM is in hand, the technolgy program will turn its attention to providing for the additional challenges that TPF poses.

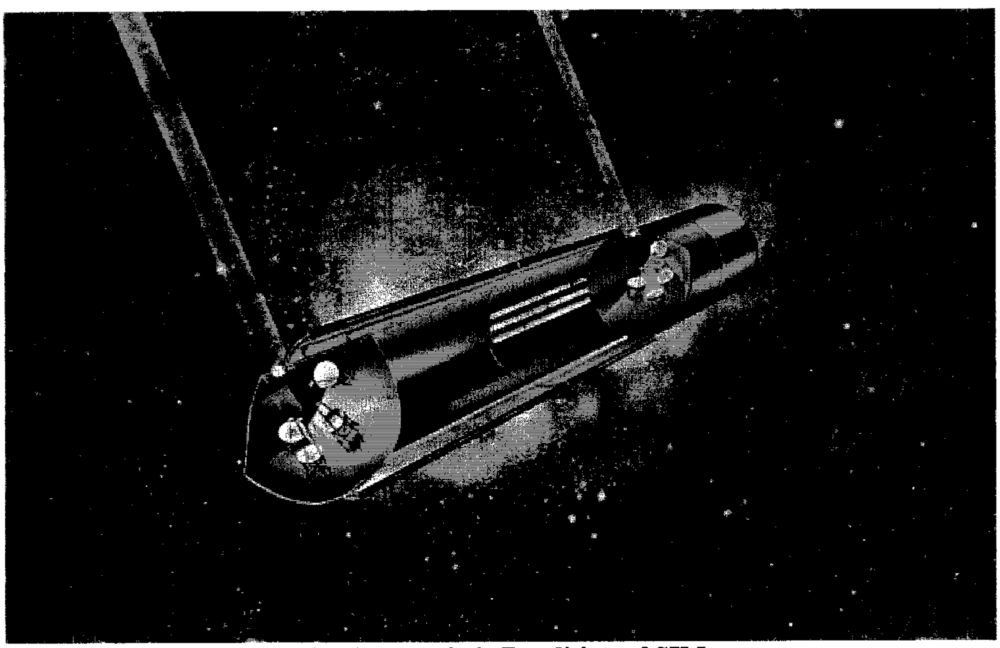


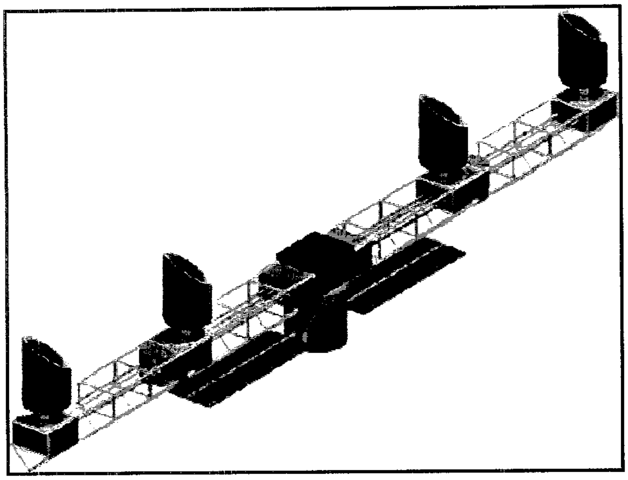
Fig. 1 Artist's Rendition of SIM

2. MAJOR TECHNICAL CHALLENGES OF SPACE INTERFEROMETRY

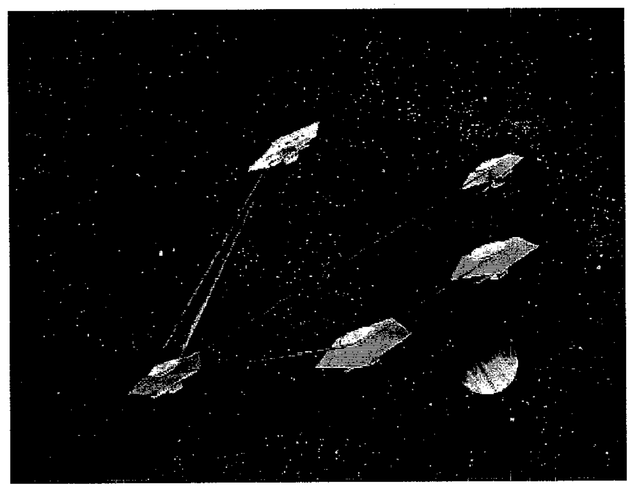
Successful development of space interferometry requires that three grand technological challenges be met and overcome:

(1) nanometer level control and stabilization of optical element on a lightweight flexible structure
(2) sub-nanometer level sensing of 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 missions. **Figure 3** illustrates the technology requirements flowdown for SIM.



Physical Baseline



Virtual Baseline

Fig. 2 Artist's Rendition of TPF

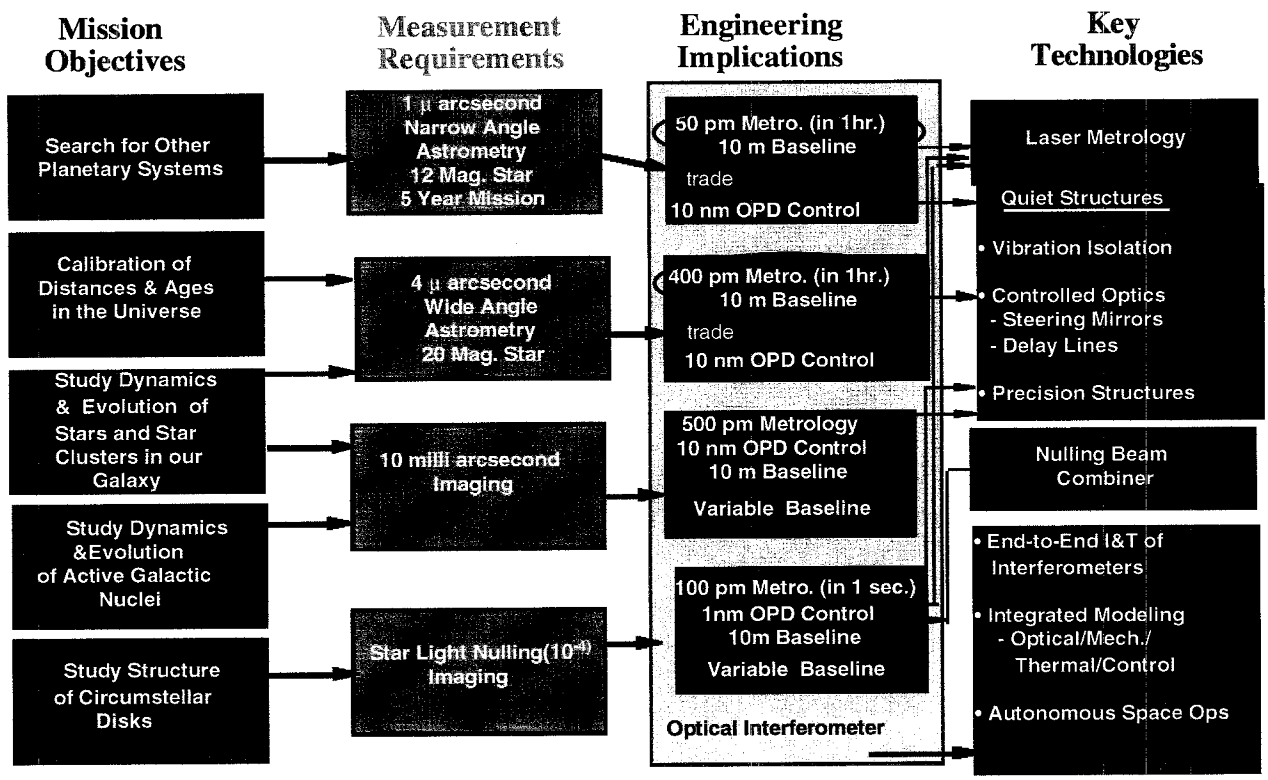


Fig. 3 SIM Technology Requirements Flowdown

The need for nanometer control is driven by requirements on fringe visibility for astrometry and imaging as well as by the requirement for 10^4 starlight nulling. The nulling requirement is the more stringent necessitating 1 nanometer RMS optical path difference (OPD) control over a broad frequency range. Fringe visibility requirements translate into the need for 10 nanometer RMS OPD control at frequencies above the fringe detector frame rate of approximately 1 kHz and more relaxed requirements at lower frequencies.

The picometer regime metrology requirements flow directly from the principal astrometry science requirements. In order to make a 4 microarcsecond angular measurement between two stars using a 10 meter baseline triple interferometer requires the relative measurement of baseline positions to 100 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 80 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 4**. An expanded set of technologies is needed for TPF (see **Figure 5**), driven by its requirements for a larger baseline and cold temperature operations (optics must be cooled to below 100°K for good performance in the 10 um range).

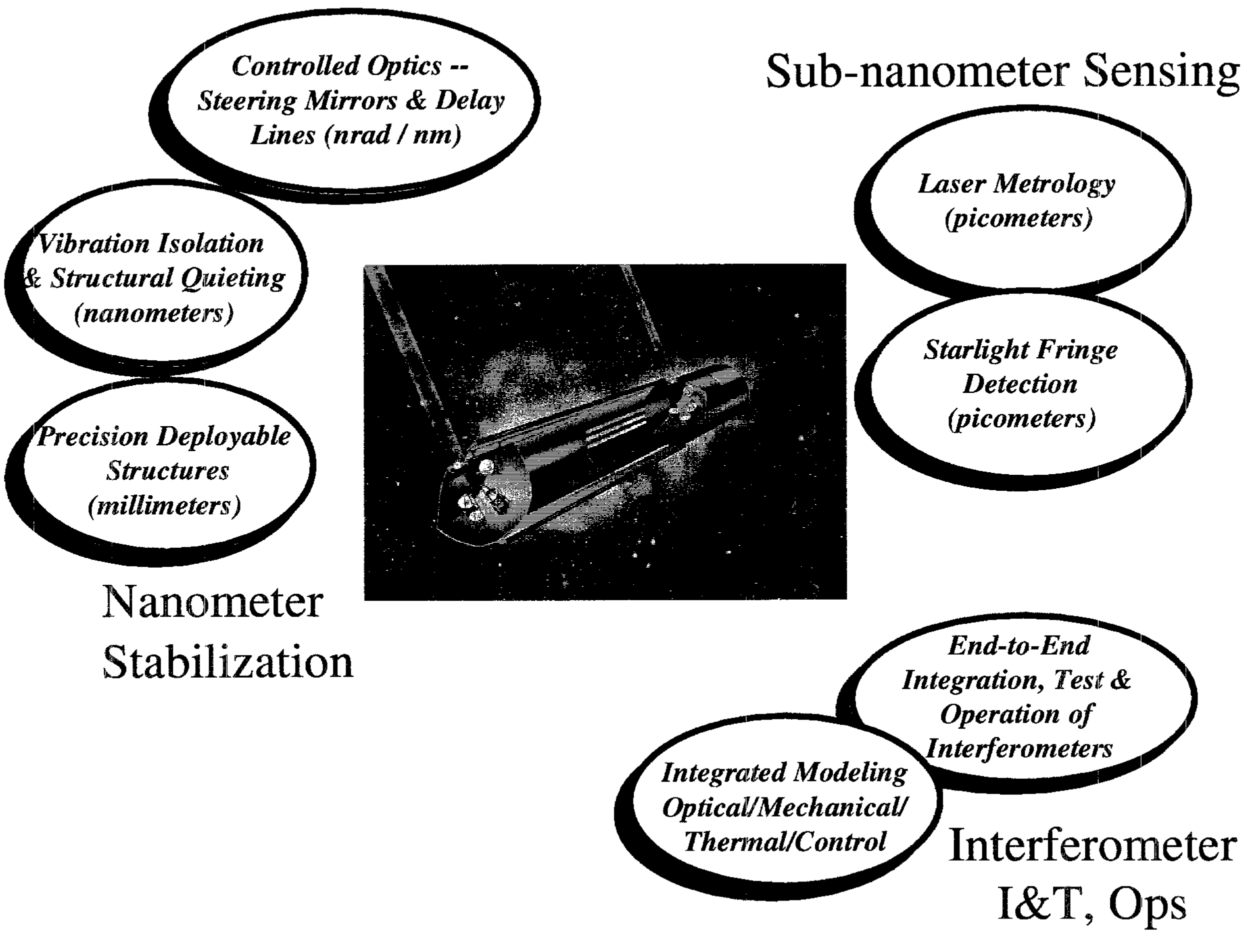


Fig. 4 Key Technologies for SIM

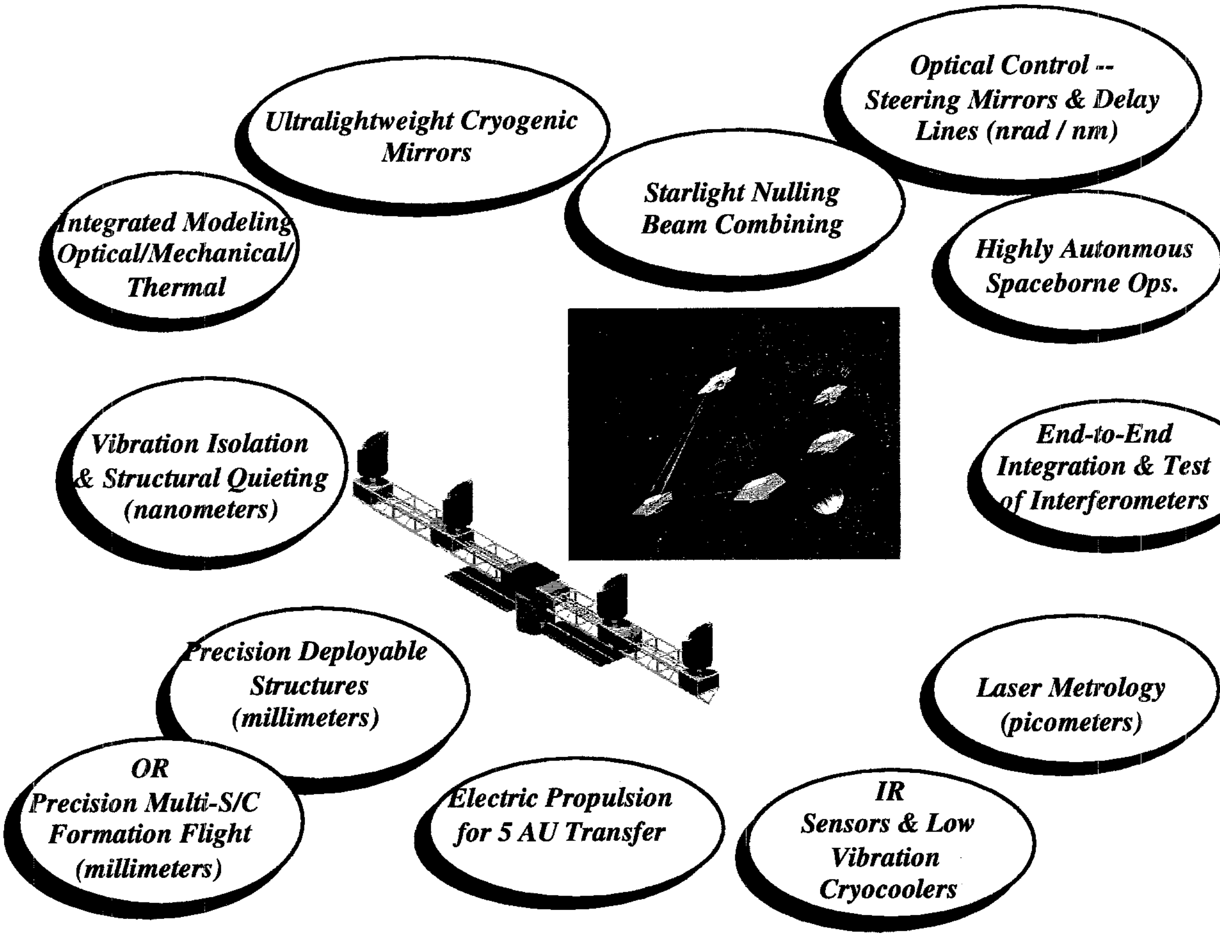


Fig. 5 Key Technologies for TPF

3. TECHNOLOGY DEVELOPMENT APPROACH

Fundamentally the approach taken to technology development is one of rapid prototyping of critcal 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 FY'00, 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. Flight experiments will in general be undertaken only where the space environment is required to explore the relevant phenomenology.

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.

For each component to be brassboarded, whether it is built in-house, built in partnership with industry, or procured in a traditional manner, a series of performance and environmental tests will be conducted whose objective it is to qualify the component design as ready for space flight. A distinction is made between qualifying the design and qualifying the component itself. None of the brassboard components are destined for flight and hence the qualification process will lack the formality (and cost) associated with flight hardware. Nevertheless the qualification process will be quite rigorous with each component subjected to full functional, shock, random vibration, and thermal (and/or thermal / vacuum) testing. JPL quality assurance and reliability personnel will be included from the outset to ensure proper test procedures. Note that only those components considered as high risk will be built and tested as brassboards. **Figure 6** depicts an example of a unit, the optical delay line, that has finished development and performance and environmental testing.

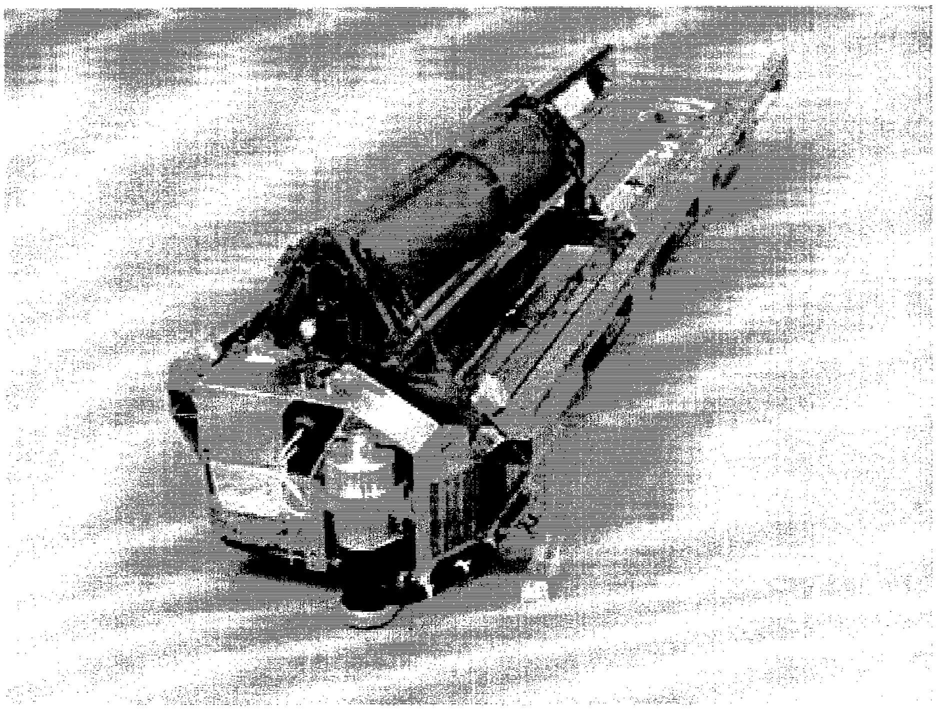


Fig. 6 Brassboard Optical Delay Line

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 analagous 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. The former is a fully functional 100 meter baseline system that has been in operation on Palomar Mountain since the summer of 1995. Built primarily as a technological precursor for the Keck Interferometer it is also in active use taking science measurements. The MPI Testbed, as will be discussed later in this paper, is a 7 meter single baseline lab emulation of a flight interferometer. It has been operational since late 1994. 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 will take place in a development environment called the Realtime Interferometer Control Software Testbed (RICST). RICST will build the code, ultimately expected to exceed 70,000 lines, in a modular fashion and will make a series of incremental deliveries. This will greatly simplify the process of testing and debugging. The initial deliveries will be internal to the RICST team and will serve to validate the development approach and train the personnel. RICST testing will incorporate breadboard and brassboard hardware allowing the software to be fully exercised by actually driving the relevant controlled components. Eventually, the RICST software will be delivered to integration testbeds (described below) where it will be 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 is a collection of functions that operates in the MATLAB environment. Currently these functions perform structural modeling and analysis, thermal analysis and optical analysis (when used in conjunction with MACOS). IMOS also incorporates several graphics functions that enable viewing of structural assembly operations, structural deformations, and element optical layouts. The core modules are easily coupled in MATLAB, and can be extended by the user by writing his/her own MATLAB functions. Additional capabilities offered by the MATLAB toolboxes for control design, signal processing and optimization further enhance the versatility of IMOS. Several interface programs have also been developed for optical analysis (MACOS), thermal analysis (TRASYS and SINDA), and finite element modeling (NASTRAN). IMOS has a limited internal optical analysis capability, and as an alternative to using the SINDA program, there is also an internal function for solving the heat balance equation.

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.

3.4 Technology integration and validation testing

In some sense the hardware and software products delineated above comprise the full set of tools and parts that the SIM Project needs to design, build and operate the interferometer instrument. However, having developed all the pieces, one huge task remains to be done -- proving that they all fit together and work as an interferometer at the relevant levels of performance. 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 Palomar Testbed Interferometer (PTI). 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-1,3. The second, i.e. the laser metrology technologies, is assigned to the MAM Testbed. PTI, an operational ground based interferometer observatory, is unique in that it is capable of viewing real stars which is necessary to validate the science data processing software.

3.4.1 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 7**) out of breadboard hardware components.

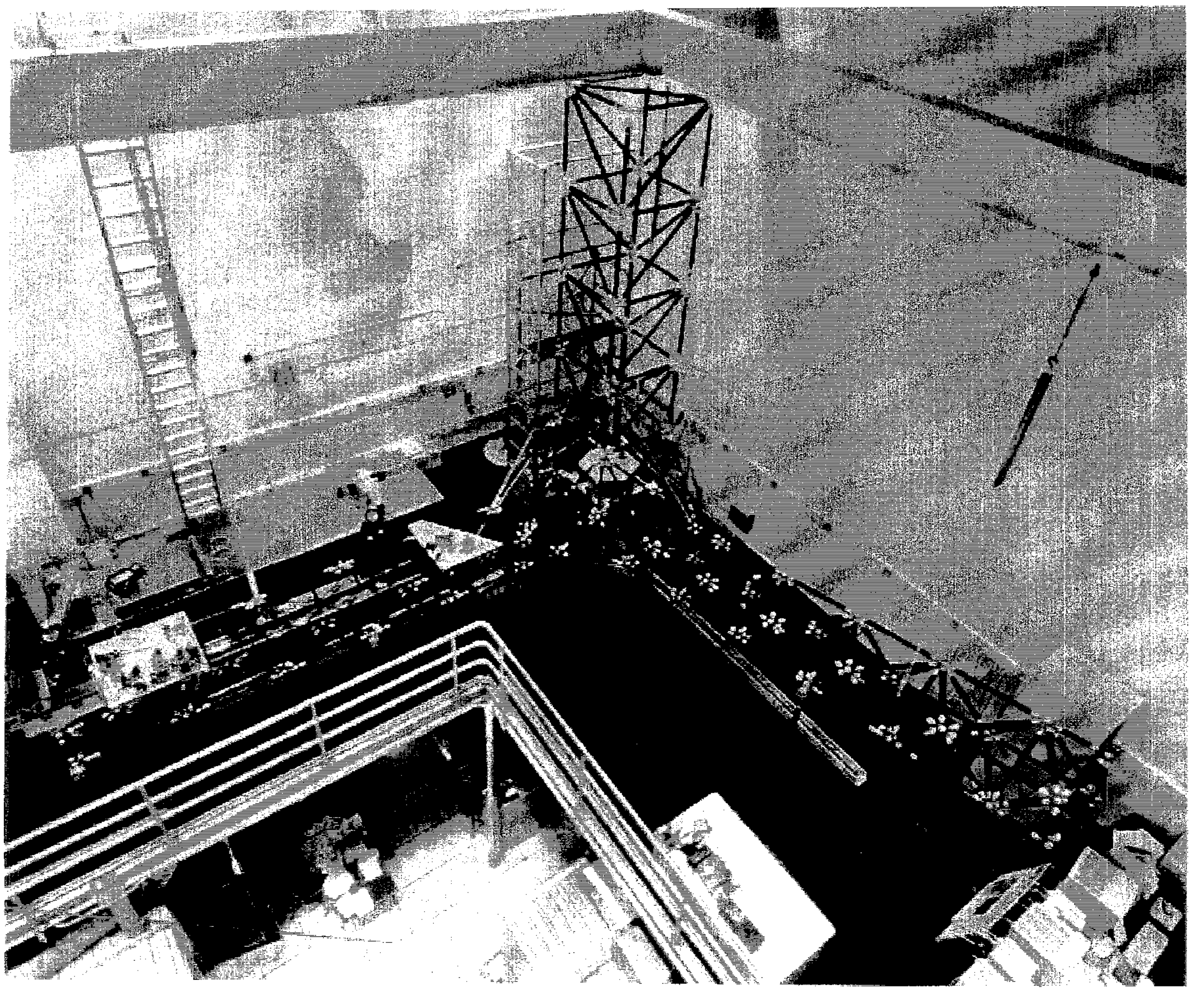


Fig. 7 SIM System Testbed - 1, Bird's Eye View

The structure is a 7m x 6.8m x 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 6 nm RMS. The goal is to achieve 1 nm by the end of the evolutionary STB program.

STB-3 is essentially a new build from the ground up. The goal is to build as high fidelity a replica of the SIM instrument as funding and SIM design knowledge can afford. Given that STB-3 will possess the same level of complexity as SIM, it represents the ultimate proving ground for RICST software. Having been wrung out on STB-3 this software should be ready for use on the flight system with only modest changes.

3.4.2 Microarcsecond metrology (MAM) testbed

The Microarcsecond Metrology Testbed will demonstrate that picometer metrology components can be configured with a stellar interferometer, per the approach of the SIM instrument, to enable the measurement of point source (viz, pseuso-star) position to the microarcsecond level. This will be done at one fifth scale in a 3-m x 13-m vacuum chamber. The MAM Testbed uses a 1.8 m baseline interferometer to observe an artificial star. The positions of the star and interferometer are monitored by an external metrology system that allows one to calibrate the star position measured by the interferometer. The interferometer includes siderostats for wide-angle acquisition, fast steering mirrors for fine guiding, a delay line for optical path control, and a beam combiner with both imaging and single-pixel detectors. The metrology system consists of nine beam launchers; two that monitor the star, two that monitor each siderostat, one that monitors the external metrology "truss," and two internal launchers that monitor the optical path length through the interferometer. The interferometer includes all of the functionality of SIM (except for switching mirrors), in a reduced scale and reduced dimensionality experiment. The MAM optics, metrology system, and artificial star are placed in a vibration-isolated, thermally stabilized, vacuum chamber. This eliminates index of refraction fluctuations in air and allows the experiment to achieve its goal of 50 pm optical path measurement accuracy.

3.4.3 Palomar testbed interferometer (PTI)

The 110 meter baseline Palomar Testbed Interferometer (**Figure 8**), in operation since July of 1995, was built primarily as a precursor and technology demonstrator for more advanced ground based interferometers like the planned Keck Interferometer.

Fig. 8 The Palomar Testbed Interferometer (PTI)

However, it has also played and will continue to play a significant role in the development of technology for space based interferometers. PTI pioneered the development of realtime software for interferometer control. Its realtime software "shell" was later adopted by STB-1 and is serving as the basis for the RICST software development approach. As a demonstration of the type of autonomy so necessary for the operation of space systems, PTI has been operated remotely from JPL, more than 100 miles away.

In the future PTI will serve as a development platform for interferometer science data processing software. Utilizing its unique dual star feed mode PTI will be able to make narrow angle astrometric measurements at accuracies under 100 microarcseconds, unprecedented for a ground based system. Such measurements will be a reasonable facsimile of the 1 microarcsencond narrow angle astrometry that SIM will perform. Hence the data processing software developed for the PTI astrometry will become the core of the SIM narrow angle astrometry science software.

3.4.4 Flight experiments

The philosophy that the Interferometry Technology Program takes toward flight experiments is to undertatke them only if the technology in question is one that cannot be validated via ground testing. The technology for deployable structures is considered to be relatively mature from the standpoint of scale (> 50 meter in length), initial deployment accuracy (millimeters), and long time scale stability over thermal loads (millimeters). On the other hand, the on-orbit short time scale stability (viz., above 1 Hz) of these systems in the nanometer regime is completely unknown. The concern is that deployable structures are dominated by hinges, latches, and joints all of which have the potential to exhibit stick-slip nonlinearities which are particularly susceptible to "creaking" due to time varying thermal conditions. Such creaking would be likely to have broad frequency content given its impulsive nature and hence, even if it occurs on the micron scale, could be quite problematic for an interferometer whose actively controlled optics might not have sufficient bandwidth to track it out.

Ground based experimental investigations into the microdynamic behavior of deployable structures is very difficult. In particular, testing in 1-g suffers from the inability to perfectly remove gravity induced internal loads from the test specimen in order to emulate on-orbit conditions. These gravity induced "preloads" could well act to completely hide the suspected stick-slip phenomena which would be unleashed only in space. This is the motivation for conducting space experimentation in order to understand the microdynamics of deployable structures.

IPEX-1 (Interferometry Program Experiment-1) was the first step toward filling the microdynamics information gap. Hosted on DARA's (German Space Agency) Astro-SPAS platform, which flew a shuttle sortie mission on STS-80 in December 1996, IPEX-1 gathered twelve channels of micro-g acceleration data using Sunstrand QA-2000 accelerometers sampled at 744 Hz. During quiet periods when thrusters were not operating, accelerations of the order of 100 micro-g's were measured. This data tells us two important facts: (i) the microdynamics of built up monolithic structures like Astro-SPAS appear compatible with interferometer mission requirements; (ii) the Astro-SPAS is a quiet enough platform to host future Origins flight experiments. The first of these, IPEX-2, was flown in August 1997, a scant eight months after IPEX-1. IPEX-2 **(Figure 9)** consisted of an instrumented portion of a representative deployable structure, a so-called ADAM-Mast built by ABLE Engineering of Goleta, California. IPEX-2 mission operations went perfectly. Over 60 channels of accelerometer, load cell, and temperature data were taken during various orbital thermal conditions including Sun-shade transitions and long duration hot and cold soaks. This data will be analyzed over the course of fiscal 1998. Taken together with ground test data the intent is to develop empirically validated analytical models capable of predicting the conditions leading to and the vibrations emanating from thermal creaks. This work will be carried out by JPL in conjuction with NASA LaRC and will involve university participation from MIT and University of Colorado.

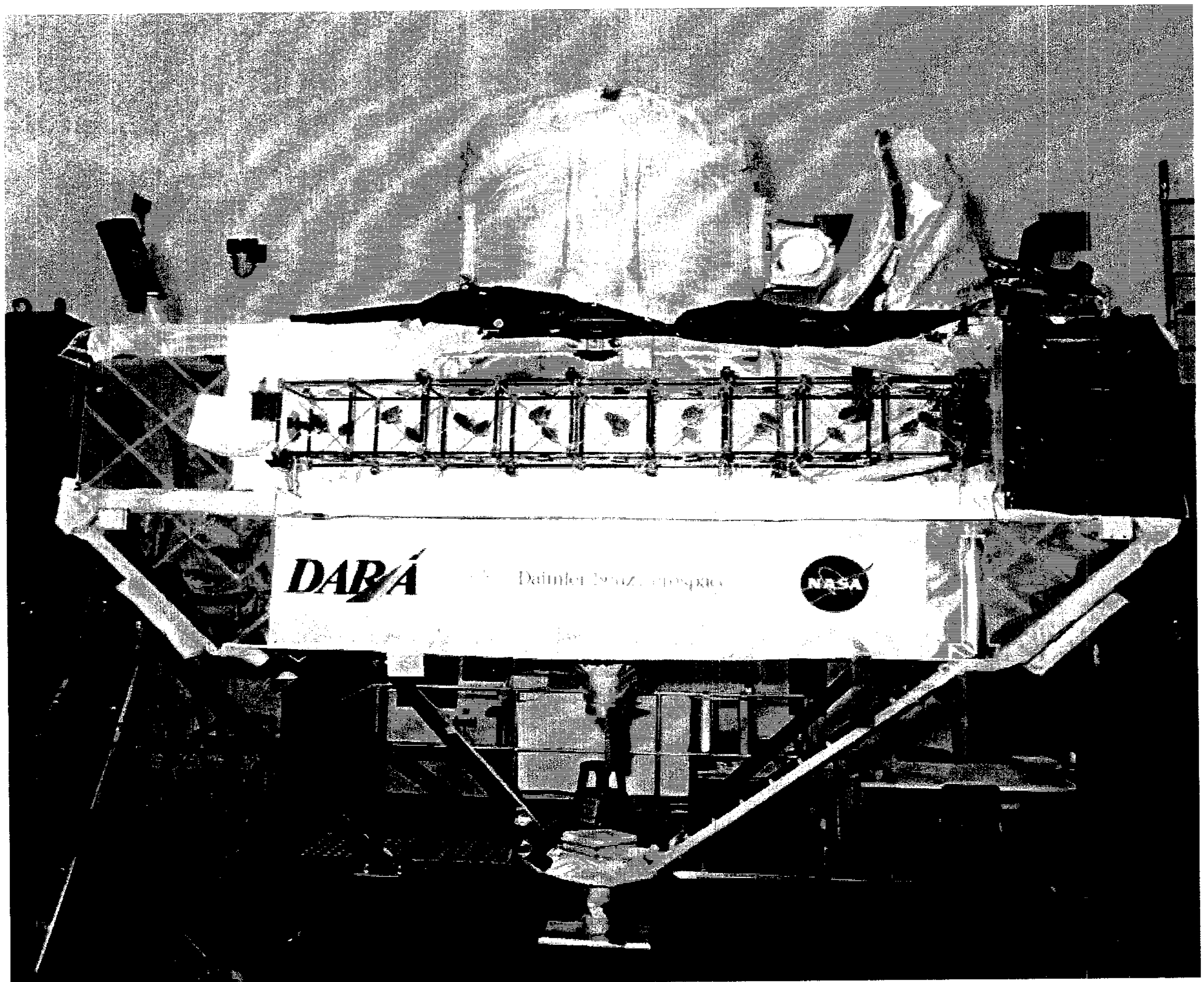


Fig. 9 IPEX-2 Integrated to Crist-SPAS and Ready for Launch

4. CONCLUSIONS

This paper has described the on-going interferometry technology development effort at the NASA Jet Propulsion Laboratory. Through the development of component hardware, prototype software, ground testbeds, and flight experiments this effort is expected to culminate in technology readiness for the Space Interferometry Mission by early in 2001.

5. ACKNOWLEDGEMENTS

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