Technology for Astrometric Detection of Nearby $1M_{\oplus}$ Habitable-Zone Planets From Space

Prepared by JPL for the ExoPTF Call for White Papers

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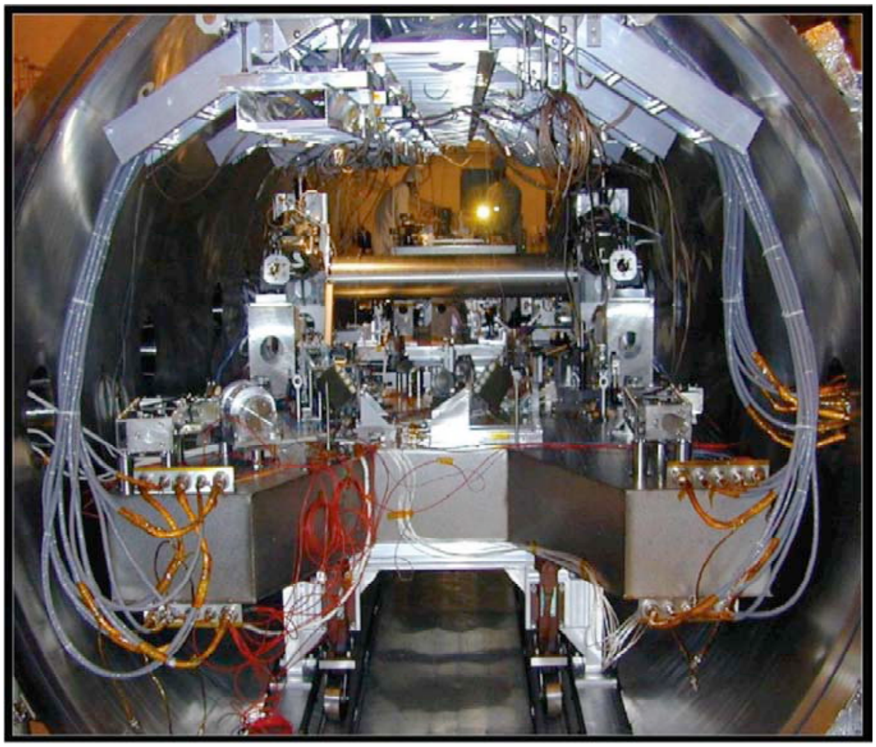
April 2, 2007



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Introduction:

Detection and characterization of one-Earth-mass ($1M_\oplus$) planets in the habitable-zone (HZ) of *nearby* stars is the ultimate objective of the NASA Navigator Program. One method of detecting these planets is ultra-precise optical astrometry with a Michelson stellar interferometer to track the motion of the star/planet-system about its barycenter over a period of time yielding mass, without M*sin(i) ambiguity, and complete orbit characterization for all planets within the range of detection (lower bound limited by astrometric precision and stellar distance; upper bound limited by mission duration and stellar distance). Detailed simulations[1,2] have shown that 1 micro-arcsecond (μas) relative astrometry provides the required capability to detect $1M_\oplus$ planets in the HZ of 100 of our closest stars over a 10-year mission (or about 65 over a 5-year mission).

This paper describes the development of the technologies needed for 1 μas astrometric precision, with a systematic error floor below 0.1 μas, as well as the tests and modeling that demonstrate confidence that the technology is complete to the point that proceeding to a full-scale mission development has sufficiently low risk. This paper also discusses the technical risk for a specific mission, SIM, relative to the use of this technology, which can be generalized to any other space interferometer mission.

The purpose of providing this overview of the interferometry technology development program is to show the high level of technical maturity of the technology as it applies to SIM and to provide sufficient information about these technologies that other planet finding projects may be able to utilize this technology to reduce development cost or risk.

Background:

Optical and infrared interferometry have been well developed for ground applications (e.g., NPOI, KI, VLTI, Chara, etc.), yet these facilities suffer limitations due to coherence size, angle and time imposed by the Earth's atmosphere. The NRC recognized in 1990 that a space-based Astrometric Interferometry Mission (AIM) capable of 30 μas performance with a goal of 3 μas, "would have a great impact on many branches of astronomy" including the ability to detect planets as far away as 500pc.[3] This mission concept was reaffirmed in 2000 in the AANM[4] and again by the CAA in 2002[5] with the added goal of achieving 3 μas (goal 1 μas) narrow-angle precision for the purpose of detection of terrestrial (rocky) planets around nearby stars. All three of these reports also recognized the benefit of AIM/SIM technology demonstrations to future space-based very-long baseline interferometers that might be capable of direct detection and eventually direct rotational synthesis imaging of planets around these nearby stars.

The challenge that NASA accepted was to convert ground-demonstrated concepts into space-capable hardware and software with sufficient reliability to enable an unattended five to ten year space based mission. A program was begun at JPL to identify and develop the necessary technologies to enable space-based interferometry missions. This technology program was later attached to the NASA Origins Program office at JPL and then to the Space Interferometry Mission (later renamed SIM-PlanetQuest) in order to provide a more direct reference mission focus to the technology development effort.

The Technology Program, under the leadership of R.A. Laskin, formed a technical advisory committee (TAC) of external experts to provide periodic assessments of the technology program's progress. The committee chair was (and still is) Robert O'Donnell (Scitor). Other members who have been with the program through a significant part of its duration include: Richard Dyer (Schafer Corp Reconnaissance Technologies), David Miller (MIT), Charles Noecker (Ball Aerospace), David Mozurkewich (then at NRL, now with Seabrook Engineering), and James Breckenridge (JPL). This committee met 3 to 4 times per year with the technology development team from 1996 through the 2005 completion of the focused SIM technology development program, and has continued with the SIM project to review the transition of the technologies into flight-like hardware.

NASA-Headquarters commissioned an Independent Review Team in 2001, later renamed the External Independent Readiness Board (EIRB), chaired by Vern Weyers (GSFC, retired), to participate in the technology assessments in order to independently evaluate and advise NASA Headquarters regarding the technical progress of the program. The EIRB continues to provide this assessment to NASA Headquarters as the SIM project transitions the technology into flight-like hardware.

Space-Based Interferometry Technology Development Program Description:

The interferometry technology development program has maintained a reference mission concept for deriving performance error budgets that are used to develop requirements allocations to hardware, software and ground processing. Initially this reference mission was a general space-based interferometer on a deployable structure. Later the decision was made to use the SIM project as a more focused reference mission because the SIM performance requirements and their mature flow down to all levels of the design provided specific requirements for the development of the technology.

The current SIM reference mission design[6] consists of one 9m Michelson stellar interferometer (MSI) for science and two 7.2m guide MSIs, which together can be thought of as a micro-arcsecond two-axis star tracker, all tied together with an external optical metrology truss. Each MSI consists of two collector telescopes, each with an off-axis 7:1 beam compressor, steering optics, optical delay lines, astrometric beam combiner, and internal metrology system used to measure internal delay. These are all standard components used in ground-based interferometers which will be subject to more challenging performance, environment, and reliability for space application.

Requirements allocations to the technology program were based upon Goal-level performance for the SIM mission as a whole (4 μas wide-angle mission accuracy over full sky and 1 μas narrow-angle single measurement accuracy over a 1° field of regard).

The technology program developed and tested components based upon these requirement allocations and then integrated them into subsystem-level testbeds that were used to verify whole branches of the error budget to ensure that there were no missing terms. Finally, system-level testbeds were developed to fully demonstrate that the components functioned as expected in a system with full complexity.

This progressive flow from components, through subsystems, to system-level testbeds [Figure-1] occurred for two paths: (1) Real-time optical-path-difference (OPD) nanometer-level control and (2) Picometer-level-knowledge sensing. The nanometer control path verified that vibrations and spacecraft attitude control induced motions could be rejected to a level that allowed acceptable interference fringe visibility (requires better than 10 nm optical path

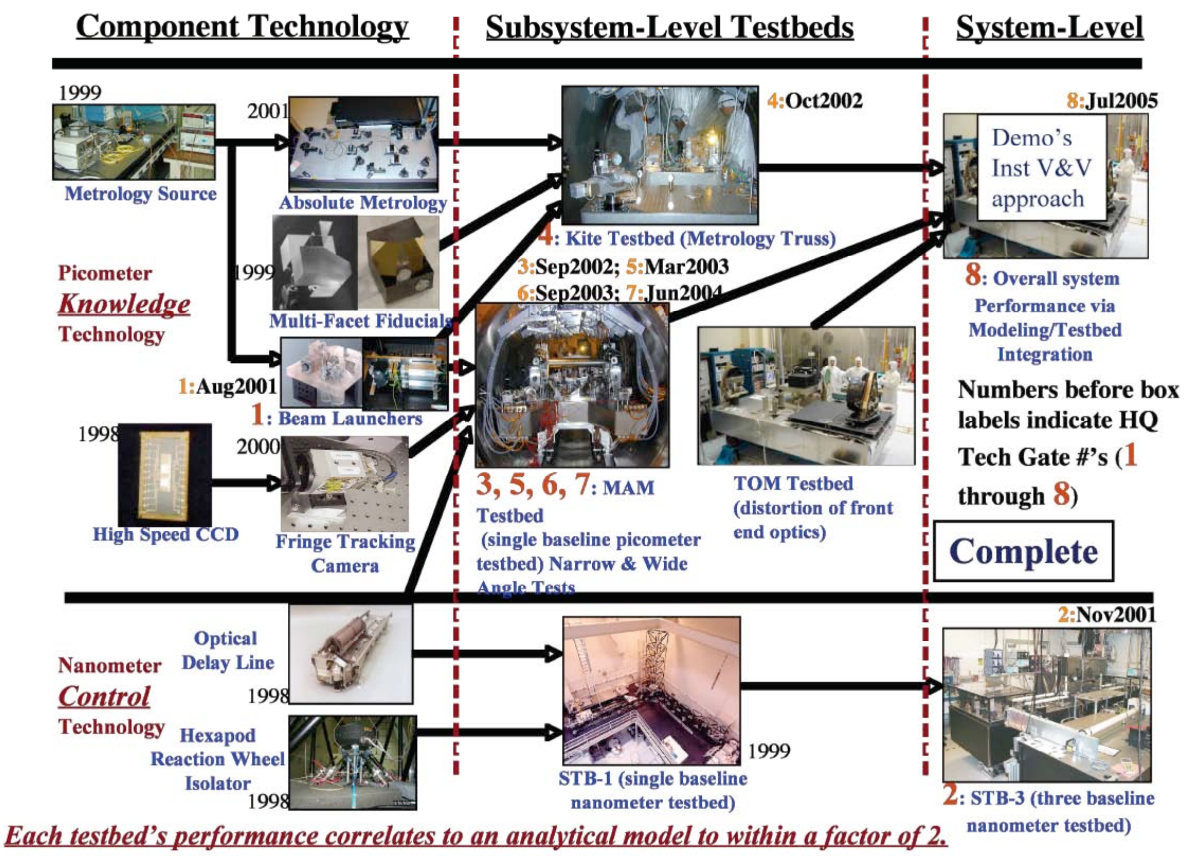

Figure 1: Technology Development Flow

difference stability). The picometer sensing path verified that dynamic displacements of optical elements within the instrument could be measured to a relative precision of a few picometers and absolute distances between elements could be measured to an accuracy of approximately one micron over distances to ten meters.

Table 1: Technology Gates with Results

Technology Gate	Description	Due Date	Complete Date	Performance
1	Next generation metrology beam launcher performance at 100pm uncompensated cyclic error, 20pm/mK thermal sensitivity	8/01	8/01	Exceeded objective
2	Achieve 50dB fringe motion attenuation on STB-3 testbed (demonstrates science star tracking)	12/01	11/01	Exceeded objective
3	Demonstrate MAM Testbed performance of 150pm over its narrow angle field of regard	7/02	9/02	Exceeded objective
4	Demonstrate Kite Testbed performance at 50pm narrow angle, 300pm wide angle	7/02	10/02	Exceeded objectives
5	Demonstrate MAM Testbed performance at 4000pm wide angle	2/03	3/03	Exceeded objective
6	Benchmark MAM Testbed performance against narrow angle goal of 24pm	8/03	9/03	Exceeded objective
7	Benchmark MAM Testbed performance against wide angle goal of 280pm	2/04, 5/04*	6/04	Met objective
8	Demonstrate SIM instrument performance via testbed anchored predicts against science requirements	4/05	7/05	Met objective

Legend
pm = picometer
mK = milliKelvin
dB = decibel (50dB = factor of 300)

* NASA HQ directed a scope increase (by adding a numerical goal to what had been a benchmark Gate) and provided a 3 month extension when performance fell short

A complete

technology plan focusing on the SIM reference mission[7] was first formally signed by the Origins Program Office in January 1998 and updated in 2003[8] and signed by NASA Headquarters. Eight (8) key technology developments from this plan were identified as "Technology Gates" with specific objectives, completion dates, and review requirements (TAC and EIRB) as a means for NASA Headquarters to carefully monitor progress. These eight gates are numbered in Figure-1 and listed in Table-1, showing a brief description of the objective of the Gate, its due date, its actual completion date, and the performance achieved.

Each of the eight technology Gates developed specific test, modeling, measurement and success criteria that were reviewed by and agreed to with the TAC and EIRB prior to testing. These formed the basis for the post-test evaluation to determine whether or not the test was successful in meeting the objectives of the Technology Gate.

Numerical modeling was a central part of the SIM technology program. Numerical diffraction modeling tools were verified for picometer accuracy over the whole range (near field, mid field and far field) using a testbed specifically developed at Lockheed Martin, Sunnyvale, CA for enabling specific test case comparison to modeling predictions. Opto-mechanical modeling tools were verified at the milli-Kelvin level, again using special testbeds developed at Lockheed Martin, Sunnyvale, CA, and at JPL in Pasadena, CA. These testbed-model comparisons showed excellent agreement (better than a factor of two over the full range of test). This experience, coupled with a similar factor of two or better performance on the subsystem and system level technology testbeds, has provided confidence in the predictive power of the modeling tools used for design and evaluation of the SIM flight system.

Another outcome of the modeling effort was the verification of the full SIM error budget, which showed consistency of the interplay between the terms in the error budget and, perhaps as importantly, showed that there were no missing terms in the error budgets (which would have shown up as un-modeled errors in the subsystem and system testbeds). This is very important in reducing the risk that there will be fundamental surprises during the flight system design, development, test and operations.

The last of the technology Gates, Tech Gate 8, demonstrated the methodology to be used for overall flight system verification and validation (V&V) where individual interferometers (science and two guides) and the external metrology system are tested to measure their individual performance in the presence of disturbances from the other elements (verifying the error budget for that whole element). Then the overall system performance prediction is generated through combining these results via the calibrated models using conservative modeling uncertainty factors (MUFs) of at least 2x based upon model fidelities actually achieved in testbeds. The logic and methodology for this buildup was carefully developed and reviewed by the TAC and the EIRB all along the way, ensuring that the V&V process was well understood and completely open to detailed scrutiny.

The technology program was completed in July 2005 and the final closeout report[9] was signed by NASA Headquarters in March 2006 after extensive review and discussion with the TAC and EIRB.

Detailed discussion of the SIM technology program can be found in recent SPIE and IAC papers by Laskin[10,11]

Engineering Milestones:

SIM continues to transition technology to flight-qualifiable hardware through a series of engineering milestones (EMs) aimed at building flight-like hardware that is environmentally

Table 2: Engineering Milestones with Results to Date

Engineering Milestone	Description	Due Date	Complete Date	Performance
Formulation Phase				
EM-1	External Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	5/31/06	6/5/06	Exceeded Objective
EM-2	Internal Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	4/30/06	5/3/06**	Exceeded Objective
EM-3	Metrology Source Assembly Validation (meet Qual environmental and allocated performance)	6/30/06	6/28/06	Exceeded Objective
EM-4	Spectral Calibration Development Unit (SCDU) (demo flight-traceable fringe error calibration methodology and validate model of wavelength-dependent measurement errors)	8/30/07	In test	
EM-5	Instrument Communication H/W & S/W Architecture Demo (validate SIM's multi-processor communications system using two brassboard instrument flight computers, ring bus, and flight software version 2.0 with specific S/W functions as listed)	4/1/07	3/5/07	Met Objectives
Implementation Phase				
EM-6	Engineering Models for Metrology Fiducials (double and triple corner cubes fully meeting SIM flight requirements)	9/30/2007*		
EM-7	Metrology Source Engineering Models (optical bench; fiber splitters; fiber switches; fiber distribution assembly; laser pump module: all fully meeting SIM flight performance requirements per table).	9/30/2008*		
EM-8	Instrument/Mission Performance Prediction (update Tech Gate #8 using latest hardware results).	9/30/2008*		
EM-9	Integration of S/C FSW build-1 with phase-1 of the S/C engineering model testbed (demonstrates specific S/W functions)	10/1/2008*		

* Completion dates deferred indefinitely due to FY07 NASA decision to delay SIM indefinitely.

** Actual signoff by NASA HQ delayed until 12/12/06 due to requests for additional thermal testing by the TAC and EIRB boards.

(when required) and performance tested to verify its capability to perform to flight requirement allocations. These flight-like hardware assemblies are called brassboards and demonstrate that flight hardware for the SIM mission can be built. Each of these Engineering Milestones (EMs) are subject to the same TAC/EIRB establishment of test and success criteria prior to testing and subject, post testing, to detailed review by the TAC/EIRB against these success criteria, exactly the same process as was used for the technology program.

Table-2 shows the nine EMs that were established for SIM, showing the five that will be completed during the Formulation phase (Phase A/B) and the four that were to be completed during the Implementation Phase (Phase C/D/E) prior to the critical design review (CDR). Of the Formulation Phase EMs, four of the five have already been completed and the final EM (#4) is on schedule to be completed by the end of 2007.

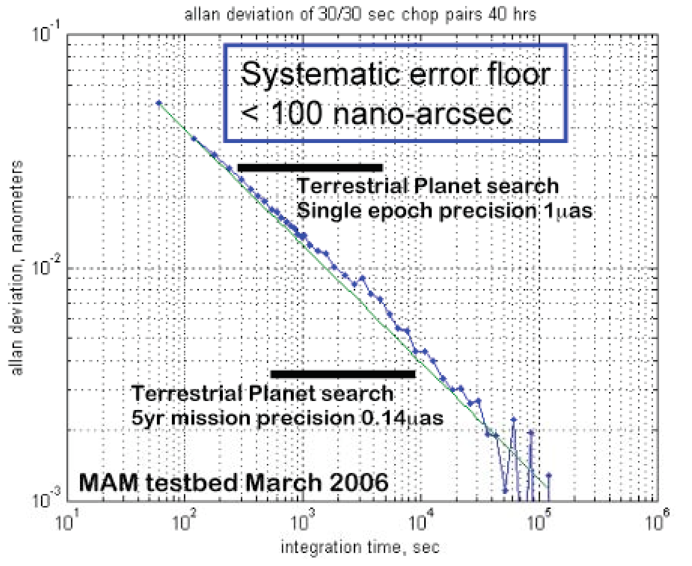

Figure 2: Systematic Error Floor

Remaining risks:

What are the remaining risks to the use of this technology (by SIM or another mission) for finding and characterizing planets?

The technology program has shown that it is possible to build all of the necessary components (hardware and software) needed for a 1 µas astrometry mission with a systematic error floor below 0.1 µas (Figure-2). It has further shown that these components

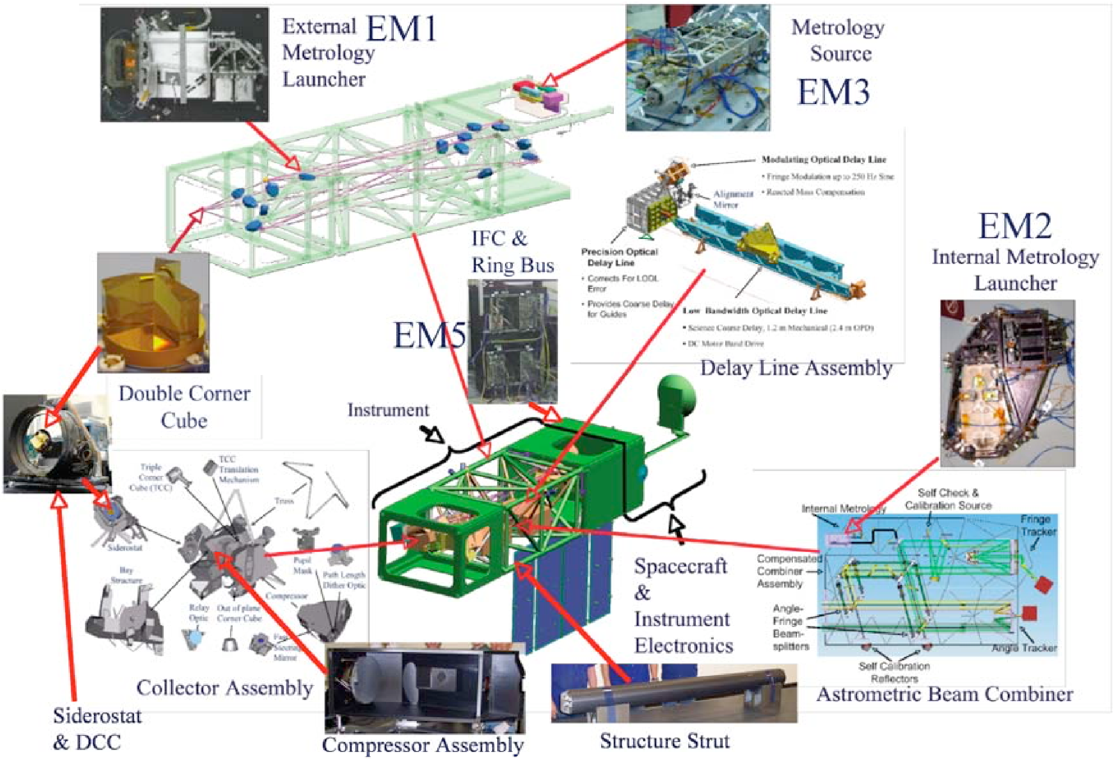

Figure 3: Flight Worthy Hardware Already Developed

work together, in a complete system, to achieve these results.

SIM's continued engineering development of these hardware components into robust flight qualifiable hardware and software (Figure-3) has shown that, even for the most sensitive picometer-hardware, these components can be built using conventional flight hardware fabrication techniques with no degradation in performance from that of the technology demonstrations.

Software development risk, at least for the SIM reference mission, has also been shown to be quite acceptable. Technology testbeds developed for SIM have demonstrated all key algorithms for control and measurement of the instrument. The fifth engineering milestone demonstrated a distributed computing environment that supports the strict timing requirements for high-bandwidth control of hardware that is distributed over a very large structure (for example, SIM or TPF). Processing of the SIM testbed measurements have taught the team how to process the instrument output to achieve the required measurement accuracy and precision in ways not anticipated early in the technology program, significantly relaxing hardware requirements. These data-processing lessons-learned should form the basis for ground processing for any flight interferometer.

Interactions between the spacecraft bus and the instrument are also well understood (for SIM anyway). These interactions include: vibration suppression (simple two-stage passive vibration isolation is sufficient), attitude stabilization for beam walk suppression (using the two guide interferometers as a micro-arcsecond two-axis star tracker to control the spacecraft attitude control system; about 10^6 times more accurate than a typical spacecraft star tracker), and torque feed-forward from the instrument to the spacecraft attitude control system to minimize attitude disturbances resulting from the motion of instrument siderostats and delay lines.

With well over $100M invested in the development of this technology, remaining risks for a user of this technology are the usual ones that occur during the implementation of any large system (manufacturing errors, interface mismatches, personnel errors, etc.).

Summary:

This paper has described a technology program and subsequent flight-like hardware builds that have retired key risks to the development and flight of a space-based long-baseline optical Michelson stellar interferometer capable of achieving the 1 μas astrometry needed to detect one-earth-mass planets in the Hz of nearby stars. All key hardware and software elements, subsystems, and systems have been demonstrated at, or better than, the performance levels required to meet the necessary 1 μas precision. The SIM project's ongoing development of hardware assemblies into flight-like assemblies continues to show that standard flight hardware development processes are sufficient for building and testing these assemblies. Currently, there are no significant technical risks to the full-scale deployment of a space-based astrometry mission similar to the SIM mission. Further information about this technology program and about the SIM mission can be found on the SIM PlanetQuest website[12].

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