Space Interferometry Mission (SIM): Overview and Current Status

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ABSTRACT

The Space Interferometry Mission (SIM) will be the first in-space, long-baseline Michelson Stellar Interferometer. SIM will perform precision astrometry at the micro-arcsecond accuracy level, which will be used to characterize planetary systems around stars within about ten parsecs of Earth and address a number of other key astrophysics projects. This paper provides a broad overview of the SIM Mission. Topics covered include: the science objectives, key top level requirements, how the mission will be implemented (technical and programmatic), technology development status, who the key players are in the SIM development, an assessment of where the project is today, and prognosis for the future.

Keywords: interferometer, interferometry, planet finding, astrophysics, space, science, mission, astrometry, SIM, Michelson

1. INTRODUCTION

The Space Interferometry Mission (SIM) is in response to the National Research Council's (NRC) Bahcall Report[1] recommendation for a space based Astrometric Interferometry Mission (AIM). SIM will continue the revolution in precision astrometry begun by the ESA Hipparcos mission by improving on the Hipparcos results by more than two orders of magnitude, providing a wealth of new astronomical data and serving as a technology pathfinder for future astrophysics missions.

SIM uses a 10-m Michelson stellar interferometer in Earth-trailing Solar orbit to provide 4 microarcsecond (μas) global astrometric position measurements of stars down to 19th (R) magnitude by the end of its 5 year mission. This precision will allow parallax measurements to 10% accuracy at 25 kiloparsec (kpc) and proper motion measurement accuracy of about 2 μas/yr over its 5 year mission (equivalent to 10 m/s at 1 kpc). SIM will also be capable of narrow angle (<1 degree) astrometric measurements that will be used to support the characterization of planetary systems around nearby stars. In addition, SIM will demonstrate the capability to do rotational synthesis imaging with a resolution sufficient to support crowded field astrometry.

This paper serves as a broad overview of the SIM Mission. Details of many aspects of the mission are covered in many of the other papers presented at this same conference[7].

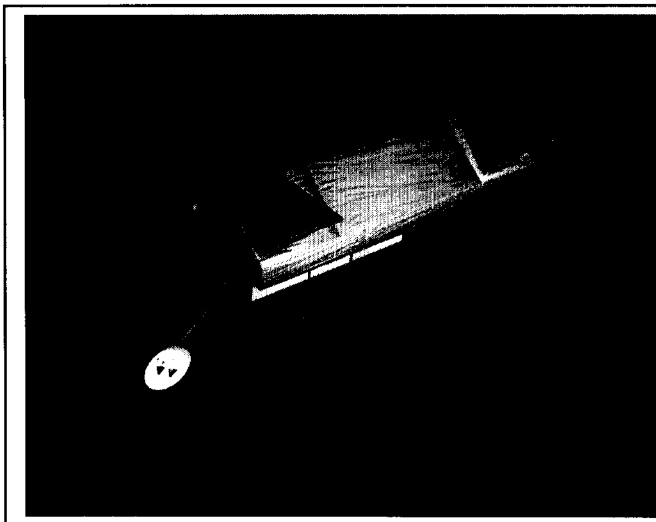

Figure 1: SIM Flight System

2. SIM MISSION SYSTEM OVERVIEW

The SIM mission consists of several systems: the Flight System, the Mission System, the Science Operations System, and the Launch System.

The Flight System (Figure-1) consists of the Spacecraft and the Interferometer packaged together into a single unit. The SIM flight system will be launched in 2009, either by the Space Transportation System (shuttle and an Integral Propulsion Module (IPM), or by an Evolved Expendable Launch Vehicle (EELV). Both options are being kept open due to the uncertainty associated with the availability of either. Either launch vehicle system will place SIM into a heliocentric, Earth-trailing solar orbit (ETSO) for a minimum 5 yr. mission life (goal: 10 year mission life).

The Spacecraft consists of structure, propulsion and avionics subsystems (antenna, telecom, power/pyro, 3 axis attitude control, command and data) provided by SIM's spacecraft industrial partner, TRW in Redondo Beach, CA.

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The SIM Instrument, which is being developed as a joint effort between JPL and Lockheed Martin Missiles and Space (LMMS), Sunnyvale, CA, consists of four, 10m long, visible-wavelength (0.4-1.0 µm) Michelson stellar interferometers. One of these interferometers is used for making science measurements, two are used to acquire bright guide stars (essentially performing as a precision star tracker or fine guidance sensor), and the fourth is a complete spare.

The Mission System will consist of standard NASA DSN based X-band uplink/downlink and navigation services, and will have separate spacecraft and instrument control centers.

The SIM Science Operations System (SSOS) will be collocated with the Interferometry Science Center (ISC), located at the California Institute of Technology (Caltech), that will be shared with NASA's Keck Interferometer (KI) project to process SIM's science data. The instrument control center portion of the Mission System is also planned to be located at the ISC with the SSOS.

More will be said later in this paper and later at this same conference[7] about most of these system elements.

3. SCIENCE INTRODUCTION

SIM's overall science objectives can be characterized as shown in Table 1.

- **Perform a search for other planetary systems by surveying 2000 nearby stars for astrometric signatures of planetary companions**
- **Survey 200 nearby stars for orbiting planets down to terrestrial-type masses**
- **Improve best current catalog of star positions by >100x and extend to fainter stars to allow extension of stellar knowledge to include our entire galaxy**
- **Study dynamics and evolution of stars and star clusters in our galaxy to understand how our galaxy was formed and how it will evolve.**
- **Calibrate luminosities of important stars and cosmological distance indicators to improve our understanding of stellar processes and to measure precise distance in the distant universe**

Table 1: SIM Science Objectives

SIM has three science measurement modes of operation: global astrometry, narrow-angle astrometry, and synthesis imaging. In both the global and narrow-angle astrometry modes, SIM has both basic-requirements and goal-requirements. The SIM team is designing to (and fully expects to achieve) the goal-requirements but, should they fail to succeed, the mission would continue to move forward as long as the basic-requirements can still be met.

Global astrometry is the process of measuring the absolute positions of objects of interest by building on a full sky grid of roughly 4000 stars that will form the astrometric Grid. SIM's basic measurement requirements are to provide 30 µas single-observation accuracy on objects as dim as 19^{th} (R) magnitude by the end of the 5-year SIM prime mission, with a goal-requirement of 4 µas accuracy. Note that 4 µas accuracy will enable measurement of distances accurate to 10% anywhere in our Galaxy.

SIM also has a "throughput" basic-requirement of <3 µas (goal <1.5 µas). This is the one-sigma, in one position coordinate, stellar photon contribution to the astrometric error appropriately scaled from a nominal R=10 star observed for 60 seconds. This "throughput" requirement ensures that excessively long integration times aren't required in order to meet SIM's measurement requirements, thus ensuring that an adequate total number of measurements can be made during the mission's limited lifetime.

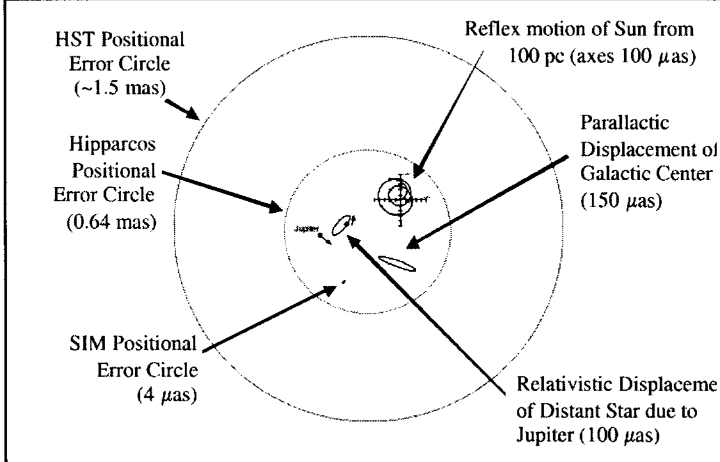


Figure 2 Global Astrometry

Figure 2 shows how SIM's global goal astrometric accuracy compares with that of the Hubble Space Telescope (HST) and the Hipparcos mission (left side figure text) and gives some examples of SIM science targets (right side figure text).

Global astrometric measurements (for both grid stars and science target stars) are made by dividing the celestial sphere into discrete, overlapping "tiles" of 15° each (Figure 3). Objects within these tiles are measured serially and tied together by the common baseline orientation as determined by the guide interferometers. Tiles overlap so that stars within the overlap region tie adjacent tiles together. Quasi-orthogonal baseline orientations are used for each tile to achieve isotropic position errors.

SIM plans to release a NASA Research Announcement (NRA) in the Fall of 2002 for selection of candidate grid stars for the SIM mission. This NRA will award one or more (perhaps as many as six) contracts for the screening of stars suitable for use as grid stars. Candidate grid stars must be identified by one-year before launch to allow the U.S. Naval Observatory (USNO) to provide the best available preliminary positions for these stars by launch.

Using SIM's "narrow angle" observing mode, with its capability to measure the relative position between nearby reference stars and the target star, SIM will detect planets around nearby stars by measuring the position displacement of each star due to motion of the star around the star-planet barycenter. The science interferometer chops rapidly between the target star and the nearby reference stars within a 1° field. Narrow-angle measurements will achieve 1 μas relative accuracy on objects to 19th (R) magnitude and will achieve 1 μas/yr. proper motion accuracy, which is equivalent to 85 mph at the center of our Galaxy and will make motion due to parallax at 10 parsec (pc) detectable in a few minutes. Figure 4 shows the expected performance of SIM in detecting planetary systems relative to the Keck interferometer.

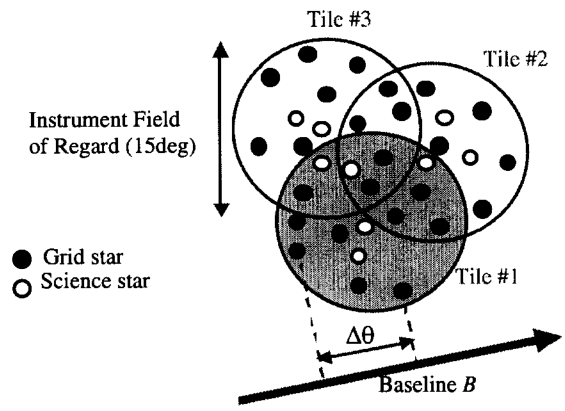


Figure 3 Global Astrometry 15° "Tiles"

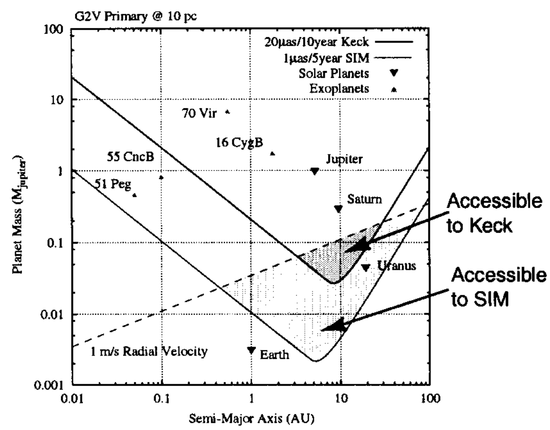


Figure 4: Astrometric Planet Detection

SIM provides limited rotational synthesis imaging capability adequate to image a few point sources located within a two (2) arcsecond (as) field. SIM's imaging capability is quite limited due to the ability to only fill in an annular portion of the image u-v plane due to all baselines being 10m long, severely limiting the low spatial-frequency content of the resulting image. The capability provided should still be adequate to assist in crowded field astrometry.

Using the measurement capability described above, SIM has a number of science measurement requirements for the mission. As mentioned above, there are basic-requirements and goal-requirements. The SIM measurement requirements are divided into four areas:

1. Planetary "Deep Search", that requires SIM to survey ≥100 (goal ≥200) nearby stars for planets down to eight (goal: three) Earth masses, including surveying the nearest dozen stars for planets down to three (goal: one) Earth masses, and to measure the orbital elements and masses of any planets discovered.
1. Planetary "Global Search", that requires SIM to survey ≥1000 (goal: ≥2000) stars for planets down to twelve Earth masses and to determine the planetary system architecture (orbital elements for all planets) for those stars already known or newly discovered to harbor planets.
1. Establish a reference frame, accurate to ≤30 μas (goal: ≤4 μas) to replace the International Celestial Reference Frame for use by a variety of astrophysical investigations.
1. Determine the positions, parallaxes, and proper motions for 4000 stars accurate to ≤30 μas (goal: ≤4 μas) for stars brighter than R=18 (goal: R=19) for a variety of astrophysical investigations.

The first part of SIM's Science Team was selected by NASA Headquarters via an Announcement of Opportunity (AO) solicitation in November 2000. From the proposals in response to the AO, ten Key Projects and five Mission Scientists were selected. Table 2 lists the Principle Investigators, their home institutions, and the topic of their proposed effort. As part of this AO, approximately 50% of SIM observing time was allocated to these successful proposals.

This first part of the SIM Science Team was selected to allow them to complete work necessary prior to launch, called "preparatory science". Preparatory science primarily falls into a few categories: (1) selection of target stars and reference stars through screening out unsuitable candidates, (2) developing algorithms for processing science data immediately following launch, (3) training a core team, and (4) attending science team meetings and other related SIM project meetings.

It is worth pointing out that because SIM science is derived from making successive astrometric measurements of stellar positions over the duration of the mission, SIM does not operate like most NASA observatories or telescopes. Except for a few targets of opportunity (ToO's) that will arise during the mission, target stars, reference stars, and grid stars must all be identified pre-launch so that astrometric observations may begin as soon as possible, following launch and continue throughout the mission. Thus, most of SIM's on-orbit observing time is spent successively repeating stellar

Key Science Projects

Names	Institutions	Topic
Dr. Geoffrey Marcy	University of California, Berkeley	Planetary Systems
Dr. Michael Shao	NASA/JPL	Extrasolar Planets [1]
Dr. Charles Beichman	NASA/JPL	Young Planetary Systems and Stars
Dr. Andrew Gould	Ohio State University	Astrometric Micro-Lensing
Dr. Edward Shaya	Raytheon ITSS Corporation	Dynamic Observations of Galaxies [1]
Dr. Kenneth Johnston	U.S. Naval Observatory	Reference Frame-Tie Objects [1]
Dr. Brian Chaboyer	Dartmouth College	Population II Distances & Globular Cluster Ages
Dr. Todd Henry	Georgia State University	Stellar Mass-Luminosity Relation [1]
Dr. Steven Majewski	University of Virginia	Measuring the Milky Way
Dr. Ann Wehrle	NASA/JPL	Active Galactic Nuclei [1]

Mission Scientists

Dr. Guy Worthey	Washington State University	Education & Public Outreach Scientist
Dr. Andreas Quirrenbach	University of California, San Diego	Data Scientist
Dr. Stuart Shaklan	NASA/JPL	Instrument Scientist [1]
Dr. Shrinivas Kulkarni	California Institute of Technology	Interdisciplinary Scientist
Dr. Ronald Allen	Space Telescope Science Institute	Synthesis Imaging Scientist [2]

Table 2: SIM Science Team from AO-1

measurements over the whole sky at intervals appropriate for the science to be accomplished. Relatively little (but still to be determined) SIM observation time is expected to remain for ToO's or other unplanned opportunities.

One year prior to SIM launch a preliminary star catalogue, a key output from the science team preparatory science efforts, will be provided to the U.S. Naval Observatory. USNO will take the preliminary star position information and provide SIM with the best known positions for these stars at the 100 masec level or better.

SIM plans to issue a second science team AO sometime in 2004 for the selection of additional science efforts that will also require preparatory efforts. The plan is to allocate between 25% and 40% of the remaining SIM observational time to the successful proposers of the second AO.

Guest Observer (GO) awards are also planned, beginning about the time of launch. The plan is to reserve between 5% and 20% of observing time for GO's, the actual fraction depending upon the science communities assessment of what science can be done through GO awards, an issue that is still open. The contract duration of these GO awards will be dependent upon what is required to support their proposal. Generally, the GO awards are expected to be for short durations of approximately one or a few years.

About 5% of SIM observing time will be reserved for the SIM Science Operations System (SSOS) to allow time for targets of opportunity or unexpected engineering events requiring instrument observing time.

4. SIM FLIGHT SYSTEM DESIGN

Figure 5 illustrates how SIM makes astrometric measurements. Shown are two telescopes, separated by a baseline, B, looking at an incoming stellar wavefront arriving at an angle, Ø, relative to the baseline. If the angle, Ø, is not 90°, light from the stellar wavefront will arrive at telescope-2 before telescope-1, due to the extra external pathlength delay, X. Assuming that the length and orientation of the baseline, B, are known, then, if the external pathlength delay, X, can be determined, the angle, Ø, can be found by simple trigonometry.

The external pathlength delay, X, can be determined by inserting an internal path delay into the interferometer's internal optical path from telescope 2. Adjusting the length of internal path delay, produced by the active delay line as shown, to match the external pathlength delay, X, allows interferometric white light fringes to form on the interferometer detector in the beam combiner. Since the correlation length of visible light from a star is on the order of a few to 10's of microns, depending upon wavelength, fringes will not be seen on the detector at all until the pathlengths are matched to within that optical path difference. Once fringes are found, the active delay line can be adjusted to track the peak in the interference fringe that occurs when the internal path delay from the active delay line equals the external path delay. Internal metrology beams then measure the optical path difference between these two arms of the interferometer providing a direct measurement of the active delay line length, which is in turn a direct measurement of the external pathlength delay, X.

The two guide interferometers track Grid stars and are used as a precision star tracker (or fine guidance sensor) to determine the orientation of the instrument baseline. The external metrology (see the metrology discussion below) is used to determine the baseline length, B, completing the information needed for astrometric measurements.

In practice, the instrument is planned to chop back and forth between a set of nearby stars, one a target star and the rest reference stars. This chopping removes errors due to slow drifts within the system (thermal, etc.). This chopping is shown in Figure 5 by the two different incoming wavefronts separated by the angle theta (θ). This chopping is compensated for by moving the delay line a distance, d, to match the new internal and external delays, resulting in the fringe remaining in lock. The relationships between the baseline, B, the true direction to the stars, Ø and θ+Ø, and the differential delay, d, are determined during ground processing of the observational data.

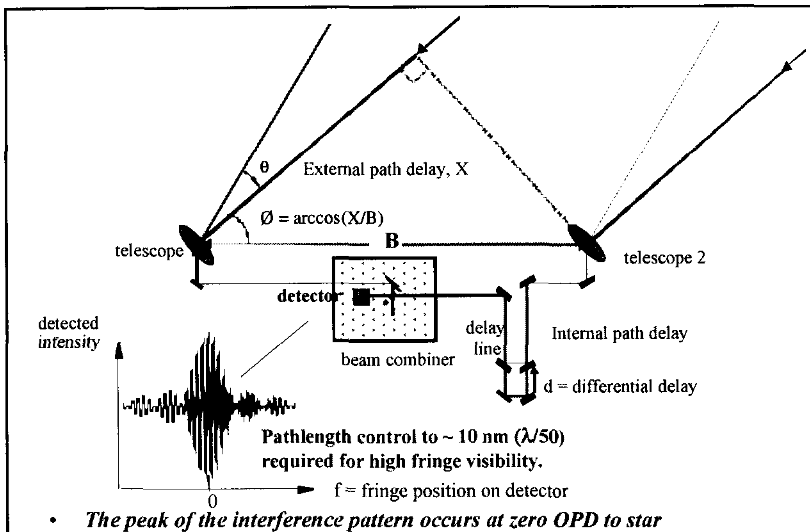


Figure 5: Astrometric Measurement

4.1 SIM Architecture

Figure 6 shows the basic elements of the SIM Flight System architecture. A single operational science interferometer, of the type described in the previous section, is mounted on (and in) a Graphite Fiber Reinforced Polymer (GFRP) Precision Structure Subsystem (PSS) that forms the optical bench for the instrument. The two guide interferometers and a complete spare interferometer are also mounted on (and in) the PSS.

The PSS is designed to be extremely stable thermally and mechanically to provide the stability needed to allow SIM's precision astrometric observations. A separate paper to be presented at this conference[2,7] describes the PSS in a fair amount of detail.

A relatively conventional spacecraft 'bus' supplied by TRW, Inc., provides normal housekeeping services (power, telecom, data collection and distribution services, and attitude control) for the entire system.

The spacecraft attitude control system is only capable of pointing the PSS at the arcsecond level while the science interferometer must be open-loop pointed to an accuracy of about 0.3 milli-arcsecond. The two guide interferometers are used to provide the information needed by the science interferometer to achieve the required level of pointing accuracy and fringe stabilization in the face of continuously-varying arcsecond-level attitude control errors.

The guide interferometers track relatively bright (8^{th} magnitude, or brighter) guide stars located nearby the target. These guide stars may or may not also be grid stars. Since the guide stars are sufficiently bright, closed loop tracking of these stars by the control systems within the guide interferometers is possible. In tracking the guide stars, the guide interferometers adjust their siderostat pointing and delay lines as required to continuously track the peak of the white light fringes for those guide stars as the spacecraft or PSS move as a result of disturbances or attitude control system hunting.

Since the science and guide interferometers are adjacent and parallel to each other on/in the PSS, the control signals used by the guide interferometers to track the guide stars are almost exactly (within calibration factors) the right signals to tell the science interferometer how to compensate its

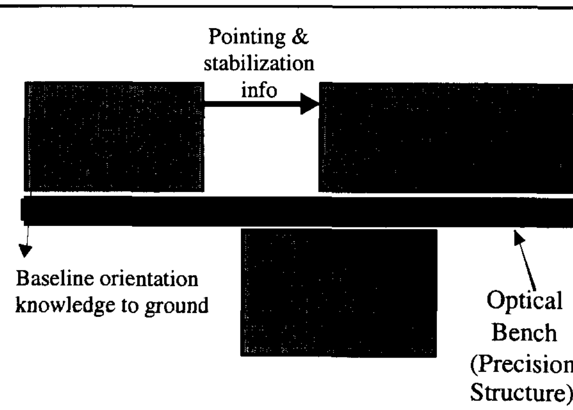


Figure 6: SIM Architecture

siderostat pointing and active delay line for the very same spacecraft and PSS motions. This "feed forward" of the recalibrated guide signals to the science interferometer allows the open loop pointing of the science interferometer sufficiently to track 19^{th} (R) magnitude science target stars.

4.2 SIM Instrument Design

The current instantiation of the general SIM architecture described in the previous section is shown in Figure-7. The collector optics for all four interferometers are housed in two optics bays at either end of the PSS structure. Within these optics bays reside the science interferometer siderostats, science and guide interferometer beam compressors that compress the collected starlight from about 30 cm down to about 7 cm, steering optics to channel the starlight from the optics bays towards the active delay lines, external metrology beam launchers and reference fiducials used to track the positions of the interferometer collector optics, and thus the baselines, at the 10's of picometer accuracy level.

The individual science or guide interferometers formed by taking the corresponding optic in each collector module each look in a different direction and have different fields of regard (FOR). FOR is the angle over which stars can be observed (may require articulation of optics) for a given baseline orientation in space. The two science (one active, one spare) interferometers have a full 15° FOR (shown by the larger cones in Figure-7) provided by the siderostats (which are only in the science and spare interferometers). The guide interferometers have a much more restricted 1° x 0.1° FOR (shown by the smaller cones in Figure-7) because they are pointed only by smaller steering optics located after the beam compressor. This more restricted guide FOR is sufficient to ensure that there is always a pair of guide stars available for any possible 15° tile and for at least two orthogonal baseline orientations. The science siderostats then provide the flexibility to observe any other grid, reference or target star within the entire 15° tile.

The three interferometers active at any one time do not all share a common baseline so baselines must be determined individually and tied together using an external metrology system consisting of 15 laser beams making measurements between optical fiducials (reflective corner cubes) attached to the face of each siderostat (which is an articulated 35 cm flat mirror used to steer light into the science beam compressors) and at the common intersection point of the guide interferometer fields of view. Each of these external metrology beams is shown in Figure-7 as lines connecting the optics in the two optics bays and as a triangle within each optics bay. These external metrology beams form an optical, redundant, truss that allows complete knowledge of the relative orientations of each guide or science interferometer baseline, providing the ability to transfer orientation knowledge from the guide interferometers to the science interferometer.

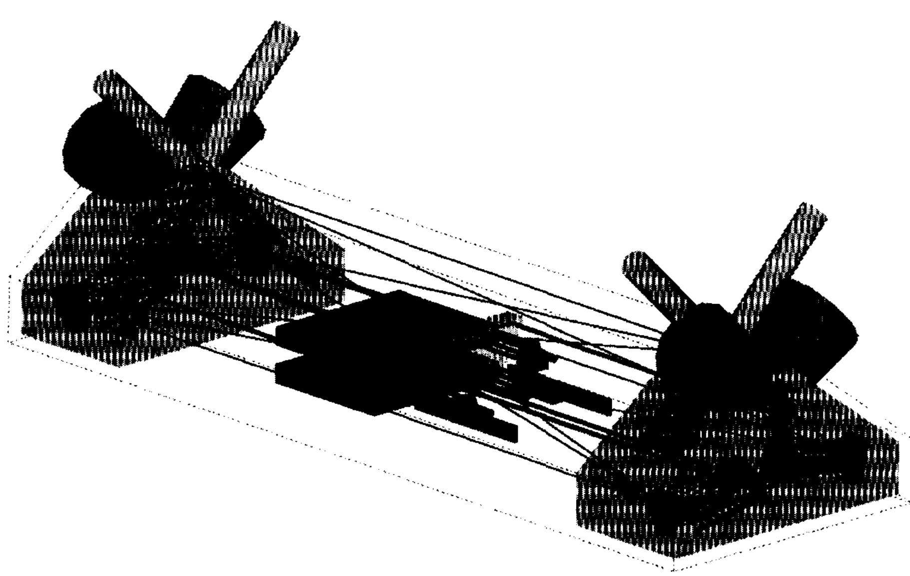


Figure 7: SIM Instrument Layout

. Shown in the center of Figure-7 are the active delay lines (to the right of the central 'block') that adjust the internal delay to be equal to the external delay and the astrometric beam combiners (the central 'block') that contain both the back-end optics and the internal metrology beam launchers used to measure the internal optical path difference induced by the active delay lines and thus to deduce the external path delay.

All of these elements are mounted within the Precision Structure Subsystem (PSS) that forms the stable optical bench for all interferometer baselines. Although not explicitly shown in Figure-7, the PSS surrounds the optics and forms the external housing as shown in Figure-1.

The SIM instrument can logically be described in terms of several 'subsystems'. These are: (1) Starlight, made up of all optical elements touched by starlight on its way through the instrument; (2) Metrology, made up of all elements of the metrology system used to measure both the positions of external optical elements and the internal pathlength differences;

(3) Real Time Control (RTC), that includes the instrument control algorithms, software and the computers and electronics required to run the software; and (4) Precision Structure Subsystem (PSS), that provides the optical bench for the entire instrument system, including thermal control and launch load support. Each of these 'subsystems' will be briefly described. Further details are available in other papers presented at this conference[7].

4.3 Starlight Optical Components

Figure-8 shows an optical schematic of all four SIM interferometers. Elements shown in Figure-8 include: (1) the four astrometric beam combiners (ABC), one for each of the two interferometers capable of performing as a science interferometer (i.e.- has a siderostat allowing full 15° FOR) and one each for the two guide interferometers; (2) the cluster of eight active delay lines (four low-bandwidth and four high-bandwidth, terms that will be explained later); (3) the relay and steering optics that transmit the compressed beam from the front end optics to the delay lines, showing all reflections in the current design; (4) the eight 7:1 beam compressors (one for each end of each of the four interferometers) that compress the beams from 35cm down to the 5 cm beam diameter propagated through the instrument; (5) the four siderostats (one at each end of the two interferometers capable of serving as a science interferometer (one is spare); and (6) the six double corner cubes that serve as fiducials for the internal and external metrology systems (one mounted on each siderostat and one at the intersection of each guide interferometer FOV). Although the internal metrology gauges are not shown (they are embedded within the ABC's) the internal metrology beams are shown as solid lines where they exit the relay optics on a path to the six double corner cubes.

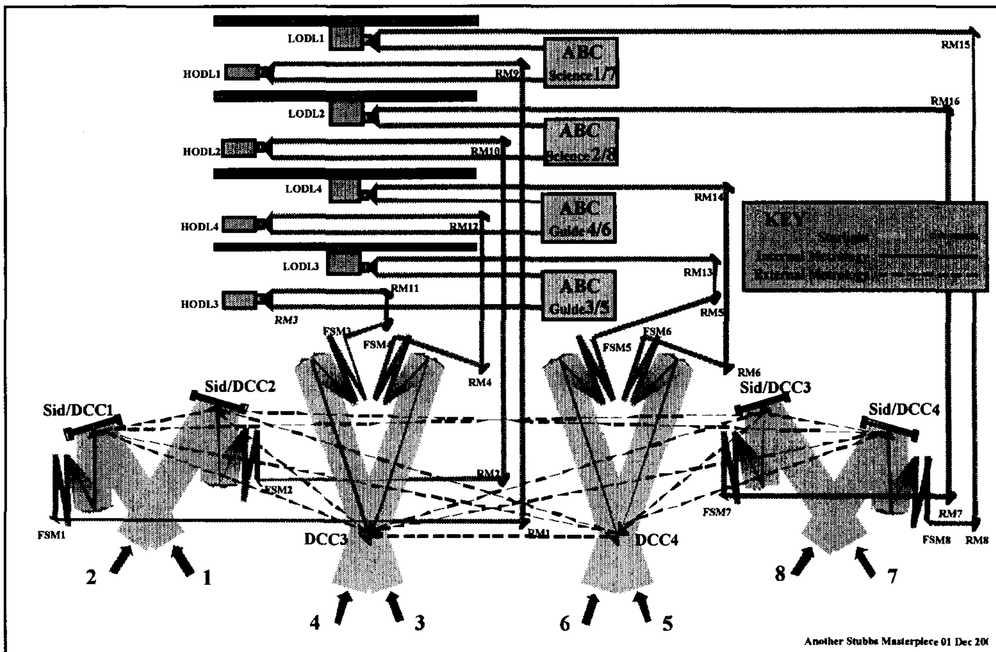


Figure 8: Optical Schematic

The optical paths from both arms of the interferometer must have high optical throughput, maintain wavefront quality and match polarization between interferometer arms in order to provide interferometer fringe visibility on the order of 0.7. Polarization matching requires that the reflections in both legs of each interferometer be identical in kind and direction.

Nanometer-level dynamic pathlength control for each interferometer is provided by a two-stage active optical delay-line. The two stages are: (1) translation along precision guide rails (~2.5m) and (2) dynamic nanometer –level real-time OPD control via a voice coil. Several versions of flight qualifiable active delay lines have been constructed as part of the SIM technology program and have been shown to provide nanometer level pathlength control.

The current SIM design splits the delay line into two physical parts, one located in each leg of the interferometer, in order to avoid having to drag cables across a moving interface. The low-bandwidth ODL (LODL) contains only the translating portion of the delay line. This portion moves only at relatively low frequency but, due to its long, ~2.5m stroke, can take a fair amount of time to effect its motion. The high-bandwidth ODL (HODL) contains the voice-coil stage of the ODL. Although the LODL and HODL are mounted in opposite arms of the interferometer, their effect is the same as though they were mounted in the same arm.

The astrometric beam combiner accepts starlight from each leg of an interferometer and provides fringe tracking and optical alignment information. It also allows launching of the internal metrology beams into each leg of the interferometer. Low noise CCD detectors that can be operated in several different readout modes are being developed for the dispersed fringe tracking cameras within the beam combiner.

Further details of the starlight subsystem are contained in the paper by Stubbs[3], et al, presented at this conference[7].

4.4 Metrology

Picometer class metrology is required to determine interferometer baseline lengths and orientations (external metrology) and optical path differences within the instrument (internal metrology). External metrology uses sub-aperture, 5mm, heterodyne laser gauges to measure the distance between optical corner cubes (fiducials) mounted on key optical elements within the instrument. A common, multi-frequency metrology source is used for all metrology gauges.

Two different metrology gauge designs are currently used in the SIM instrument. Both stem from common ancestor of a gauge developed at JPL to measure optical surface quality known as the COPHI experiment.

External metrology uses a gauge referred to as the QP gauge (originally standing for 'quick prototype', describing where the gauge design was originally developed). This metrology gauge launches and detects a sensing beam that makes a round trip between two optical corner cubes in a "race track" manner such that the incident and return beams do not overlap. The design of the QP launch supports two gauges, rotated 90°, so that external metrology beams can be redundant, if necessary.

Internal metrology uses a gage known as SAVV (sub-aperture vertex to vertex). This gauge is a differential metrology gauge that launches beams from the Astrometric Beam Combiner (ABC) out to the corner cube fiducials at the end of each interferometer arm and thus measures the optical path difference between the interferometer arms. The optical path difference is the only information needed to control the active delay lines and to infer the external pathlength difference for starlight arriving at the two siderostats.

A complex laser source has been developed that produces not only the two separate frequencies required for operation of both QP and SAVV type metrology gauges, but also provides another reference frequency that enables absolute (as opposed to relative) metrology measurements of distances within the external metrology truss. Laser lifetime is a significant issue for a mission that hopes to achieve a 10 year on-orbit life and an approach has been developed that appears to have the capability to meet SIM's lifetime requirements.

For further information on the SIM metrology system, see the paper by Stubbs[3], et al, presented at this conference[7].

4.5 Real-Time Control (RTC)

The RTC subsystem includes the computers, other electronics, and software needed to run the interferometers.

Analogues of the RTC subsystem are currently running on two of the SIM system-level testbeds and appears capable of performing all required SIM functions with available flight-qualifiable electronics.

Further information on the RTC subsystem is provided in the paper by C.E. Bell[4] presented at this conference[7].

4.6 Precision Structure Subsystem (PSS)

SIM requires a dynamically quiet, thermally stable structure. Excellent structural and thermal stability, while not simple to achieve, appears to be within current state of the art.

The current design of the SIM Flight System has no deployables associated with the instrument (the only deployable elements being the spacecraft solar array and the spacecraft high gain antenna, both isolated from the instrument by passive isolators), a significant simplification from earlier Flight System designs that had fairly complex deployments with resulting concerns about microdynamics being generated from thermal stresses at the deployment joints.

The SIM structure will use a Graphite Fiber Reinforced Polymer (GFRP) structure provided by Composite Optics Inc. With a sufficiently low temperature coefficient (10^{-7}/°C) that makes possible simple but adequate temperature control of the structure. A thermal control scheme has been developed that provides 0.1°K thermal control of the entire structure, which is more than adequate to meet SIM's stability requirements.

Figure-1 shows the basic elements of the PSS, including: (1) the basic 10m structure with triangular cross section; (2) the "backback", mounted below the basic structure, that contains all spacecraft subsystems and the instrument RTC subsystem; (3) the deployable sun shades that protect each optics bay during launch and, following their deployment; allows the sun to be anywhere in the hemisphere below the plane, defined by the top of the openings of the sun shields and (4) the deployed high gain antenna and solar array.

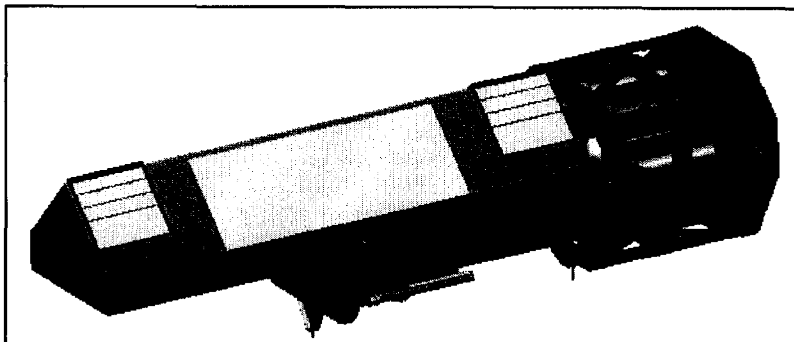


Figure 9: SIM with IPM stowed for STS launch

Figure-9 shows the Flight System packaged for launch on the Shuttle along with the Integral Propulsion Module (IPM) liquid propellant engine derived from the

Chandra mission that would be used to boost the SIM Flight System from Low Earth Orbit (LEO) into Earth Trailing Solar Orbit (ETSO) (note, the IPM would not be required for an EELV launch). The sun shades are shown in their stowed configuration.

Further information about the PSS is provided in the paper by D. Brady[2] presented during this conference[7].

4.7 Modeling

The SIM instrument pushes optical, control and knowledge technology on several fronts. Many of these fronts are being addressed through both analytical and physical modeling.

At the top level are models used to determine the appropriate performance specifications for the integrated flight and ground system to enable the required level of performance over SIM's lifetime. The primary model for this is referred to as SIM-sim for SIM-simulation. This is an end-to-end simulation of SIM starting with an input grid of stars with pre-determined positions, modeling the flight system observation sequence and on-board data reduction with injected colored observation noise, and then processing the data on the ground as currently planned to produce a set of estimated positions for the input grid of stars. These estimates are then compared to the a priori input positions to determine mission capability. Simulations done so far with SIM-sim confirm that, at least for global astrometry measurements, if SIM is capable of meeting its measurement performance requirements, then SIM will produce the required levels of global astrometry. Further information regarding SIM-sim is available in a paper by Meier[5] presented at this conference[7].

Another class of models deals with understanding the effects of reaction wheel vibration disturbances on instrument fringe visibility, including the effects of mitigation approaches such as the two-stage passive vibration isolation system planned for SIM. Analytical models have been developed and compared with actual data taken from the technology development testbeds specifically designed to verify that the instrument is capable of achieving Optical Pathlength Difference (OPD) control at the nanometer level. These models and testbeds are essentially complete and have verified that OPD control at the required levels is achievable.

Yet another class of models deals with picometer-level effects, mostly pivoting around optical diffraction. Much of SIM optics operates in the region between where near-field or far-field approximations work, requiring analytical modeling and the development of a diffraction testbed to verify the nature of the predicted effects. Since modeling a complex optical path at the picometer level is not expected to ever predict the fine details at the picometer level, these efforts are looking for the integrated effects of the diffraction field over OPD's of interest and have been quite successful. For further information, refer to other papers given at this conference[7].

Still other models are used to predict specific optical, thermal, or mechancal effects in support of technology development or flight system design. These are many and will not be covered here other than to say that they are an essential part of the SIM design development process.

4.8 Spacecraft

The spacecraft (S/C) engineering bus, to be developed by TRW, provides standard engineering services to the SIM instrument, including:

- Power: Gimbaled 4 kW solar array,
- Telecom: X-band with high and low-gain antennas,
- Command and data handling:
  - Onboard data storage: 48 GB solid state recorder,
  - Uplink command/sequence decoding and distribution,
  - Downlink of science and engineering data,
- Coarse attitude determination and control:
  - 2-axis coarse digital sun sensors,
  - Precision star tracker,
  - 4 reaction wheels mounted on passive vibration damping systems,
  - Monoprop for reaction wheel unloading sufficient to support the 10 year goal mission.

Spacecraft subsystems are expected to use available off the shelf elements whenever possible to reduce non-recurring costs.

The spacecraft subsystem components are all mounted in a "backpack" with the instrument RTC electronics. This backpack can be seen in Figure-1 as a box structure mounted on the lower surface of the PSS from which the high-gain antenna and solar arrays are seen protruding. Passive vibration isolation is provided between the "backpack" and the PSS, yielding two stages of passive isolation (the other is the wheel mount passive isolators) between the reaction wheels and the PSS, ensuring adequate attenuation of wheel disturbance vibrations.

The SIM spacecraft will provide the command and control functions to the Integral Propulsion Module (IPM) shown attached to the stowed SIM flight system in Figure-9. The IPM is a bi-prop module derived from the Chandra mission (formerly knows as the Advanced X-ray Astronomic Facility, or AXAF for short) boost engine design. This engine is only propulsion and needs the SIM spacecraft to provide all power, command and control and attitude control functions for the module. Recall that the IPM will only be used in the event of a SIM launch aboard the Space Transportation System (STS).

4.9 Integration and Test

Instrument integration and test will be accomplished at the Lockheed Martin, Sunnyvale, CA., facilities, under Lockheed Martin leadership, due to the need to use the large Lockheed Martin Delta-chamber to house both the flight instrument and the inverse-interferometer pseudostar required to test the instrument performance.

Spacecraft integration and test will be accomplished at TRW facilities in Redondo Beach, CA., under TRW leadership.

Following completion of the separate instrument and spacecraft integration testing, the spacecraft will be shipped to Lockheed Martin, Sunnyvale, where full flight system integration and testing will take place under TRW leadership.

The flight system will then be shipped to the Kennedy Space Center (KSC), FL, for final functional verification and launch readiness testing and final assembly to the launch vehicle.

5. LAUNCH AND MISSION OPERATIONS

Launch vehicle and launch operations will be handled either by the Johnson Space Center (JSC) with the assistance of the Kennedy Space Center (KSC) in the event of a STS launch, or by the KSC directly in the event of an EELV launch, but in either case under the supervision of TRW, SIM's Assembly, Test, and Launch Operations (ATLO) manager.

Launch will be from the Eastern Test Range at the Cape Canaveral Air Station in 2009 into an Earth Trailing Solar Orbit with a drift away rate of approximately 0.1 AU/yr., reaching a maximum communication distance of 95 million kilometers after 5 years. Flight system velocity will be determined from ground based ranging and Doppler data to an accuracy of 20 mm/sec or better to allow correction for stellar aberration. Science observations will be made at any angle greater than 50° from the Sun to avoid thermal impact from Sun illumination of instrument optics.

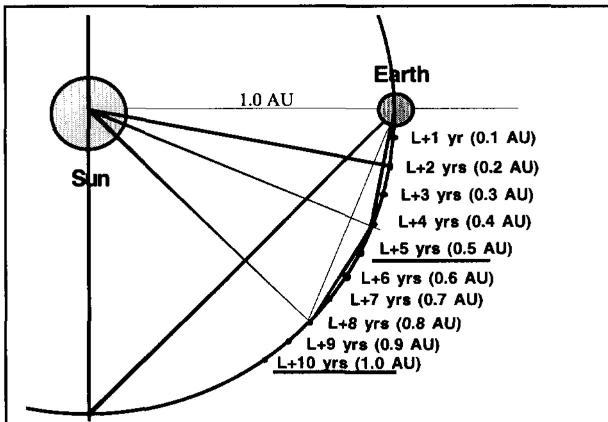


Figure 10: Earth Trailing Solar Orbit

With about 70 gigabits of downlink required per week, the downlink data rate will depend upon the range from Earth and the Deep Space Network (DSN) antenna coverage available (Table-3). During the early part of the mission, the roughly 8 hours per week required for Doppler ranging will drive the DSN antenna coverage requirements. By the third year of operations, DSN antenna coverage requirements will be driven by the downlink data rate, increasing to nearly 21 eight-hour 34m antenna tracks per week at the end of the 10 year goal mission.

Range [AU]	34m Ant Cap [Kbits/sec]	34m Rqmts [hrs/wk]	34m Rqmts [tracks/wk]
0.1	2200	8*	2 @ 4hr ea
0.2	2150	8	2 @ 4hr ea
0.3	950	15	3 @ 5 hr ea
0.4	530	27	6 @ 5 hr ea
0.5	340	42	6 @ 8 hr ea
0.6	240	60	8 @ 8 hr ea
0.7	175	81	10 @ 8 hr ea
0.8	130	108	13 @ 8 hr ea
0.9	105	135	18 @ 8 hr ea
1.0	86	165	21 @ 8 hr ea

Table 3: DSN Antenna Coverage (@ 0.1 AU/yr Drift

During in-flight operations, uplink, downlink, and Navigation services will be provided by NASA's Deep Space Network and JPL's Deep Space Mission Services (DSMS) organization using standard multi-mission services tailored to meet SIM specific needs.

Spacecraft engineering system operations will be conducted from JPL and supported by TRW personnel. Instrument operations and science data reduction will be done at the Interferometry Science Center (ISC) at the California Institute of Technology, Pasadena, CA, USA, with support from the JPL and Lockheed Martin development teams.

The first thirty (30) days of in-flight operations will be used to check that the flight and ground systems are operating normally. This period will be followed by about five (5) months of in-orbit checkout (IOC), during which the SIM instrument in-flight calibration will be performed and the instrument made ready for normal flight operations. Following IOC, formal science operations will begin.

Science operations will be conducted a "tile" at a time (see Figure-3), with each tile taking about one hour to complete, including slew and settle time. The entire sky will be repeatedly observed, one 15° tile at a time throughout the remainder of the mission, punctuated periodically by target of opportunity (ToO) observations, such as micro-lensing events.

Since science target star and grid star observations will be taken during each tile of observations and many successive observations of both grid and science stars are required before science conclusions or discoveries can be made, the data from observations is collected, corrected with calibration data and stored in the SIM Science Operations System (SSOS) and the Caltech Inteferometry Science Center (ISC) until sufficient observations have been completed to allow batch processing to take place. The frequency of this batch processing and the frequency of public release of science data or results is yet to be determined.

6. TECHNOLOGY DEVELOPMENT

SIM has technology challenges in three areas: (1) nanometer level control and stabilization of optical elements on a lightweight flexible structure, (2) sub-nanometer level sensing of optical element relative positions over 10 meters of separation, and (3) overall instrument complexity and the implications for interferometer integration & test and autonomous on-orbit operation.

SIM technology development has been approached in three major clusters of testbeds: (1) components, (2) nanometer control testbeds, and (3) sub-nanometer knowledge testbeds.

Component technology development is now considered complete. Those component technologies are listed in the left hand part of Figure-11.

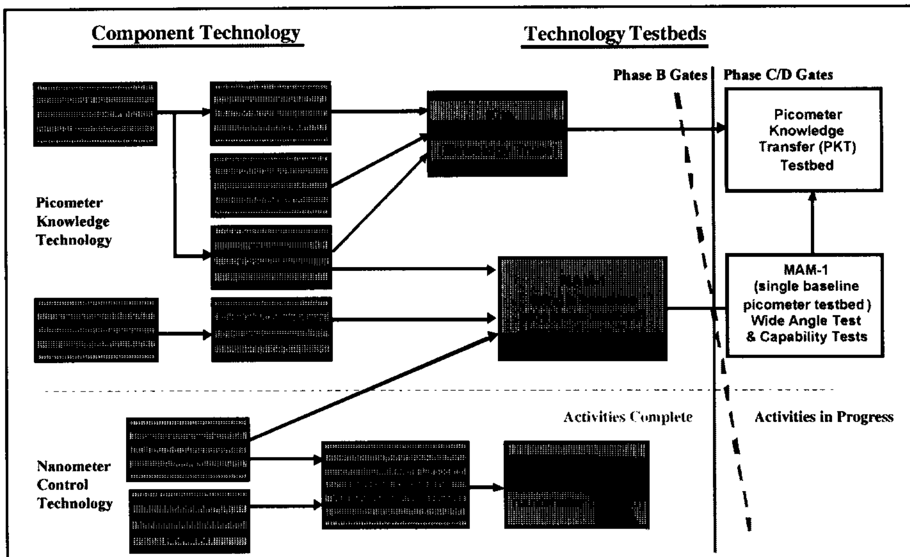


Figure 11: SIM Technology Development Progression

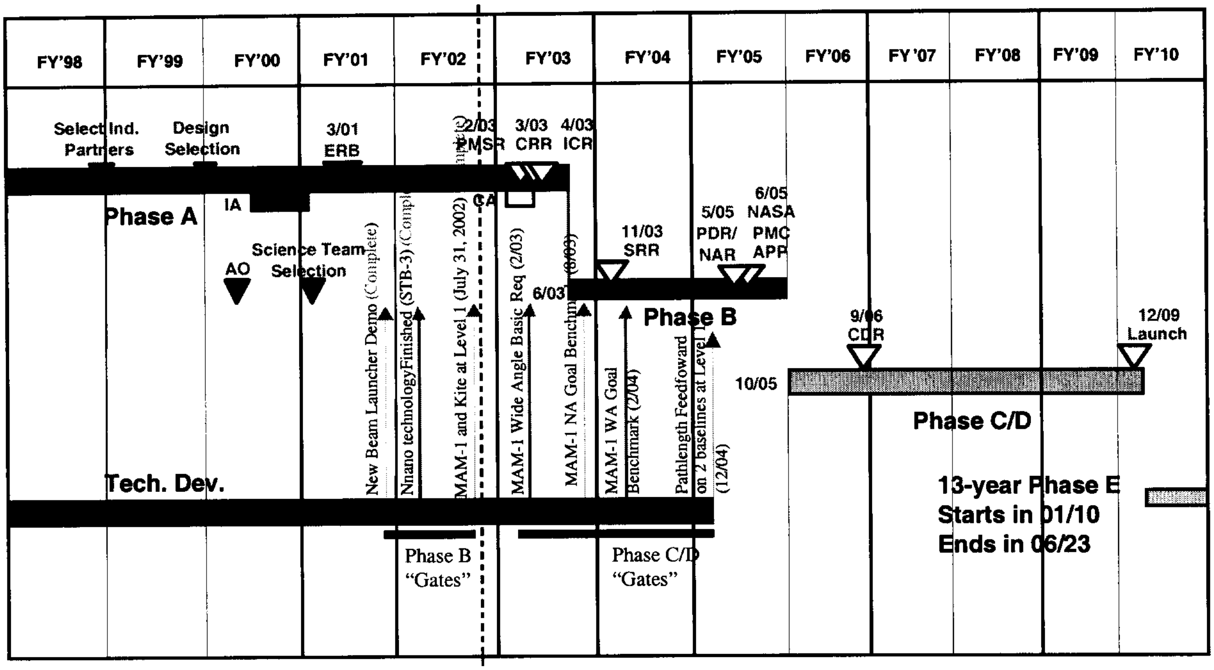
Similarly, the nanometer control testbeds are also considered complete. These testbeds are STB-1 and STB-3 as shown in Figure-11. STB-1 is a single-baseline half-scale interferometer on a flexible structure that has been used to verify reaction wheel isolation approaches and to validate analytical model predictions of that isolation. STB-3 is a full three-baseline half-scale interferometer with a simulation of spacecraft attitude control disturbances to verify that the guide interferometers attenuate those disturbances in the science interferometer to better than 60 dB (now complete). STB-3 requires full instrument control functionality but not sub-nanometer knowledge.

Sub-nanometer knowledge technology demonstration is being performed on a suite of testbeds. The first of these is the Kite testbed that is in the process of verifying that an external metrology truss is capable of transferring sub-nanometer knowledge from one interferometer to another using an over-determined truss of six QP metrology gauges. The MAM-1 testbed, also currently underway, is a one-fifth scale, single-baseline interferometer that is being operated in vacuum with a plane wavefront pseudostar to verify that sub-nanometer knowledge of fringe position in the Astrometric Beam Combiner (ABC) is possible. Currently in planning is a sub-scale, two-baseline Picometer Knowledge Transfer (PKT) testbed that will verify sub-nanometer knowledge transfer from a guide interferometer to a science interferometer.

Both the MAM-1 and PKT testbeds are expected to complete demonstrations by mid-2005 at which time the SIM technology program will be complete and the SIM project will be ready to proceed into full scale development (Phase C/D).

Based upon the SIM error budget and the demonstrated technology to date, SIM astrometric performance is predicted at 3.2 μas global astrometry (vs a goal performance of 4 μas) and the narrow angle astrometry performance is predicted at 1.7 μas (vs. a basic requirement of 3 μas and a goal requirement of 1 μas). Thus, assuming that current technology can be converted into long-life flight hardware, predicted SIM performance exceeds the goal global astrometric performance requirement and nearly meets the goal narrow angle astrometric performance requirement.

A much more expanded treatise on SIM technology can be found in the paper by Laskin[6] presented at this conference[7].



ATLO = Assy, Test & Launch Ops
CA = Confirmation Assessment
CDR = Critical Design Review
CR = Confirmation Review (NASA PMC)
ERB = External Review Board
IA = Independent Assessment
I&T = Integration & Test
PMSR = Preliminary Mission & Systems Review
NAR = Non Advocate Review
PDR = Preliminary Design Review
NASA PMC = Programmatic Management Council (APP = Approved)
SRR = System Requirements Review
CRR = Confirmation Readiness Review (JPL PMC)
ICR = Initial Confirmation Review (Code S)

Figure 12: Top-Level SIM Schedule

7. PROGRAMMATICS, CURRENT STATUS, AND PROGNOSIS FOR THE FUTURE

Figure-12 shows the current SIM development schedule. SIM started NASA's Formulation Phase, consisting of Phases A (Mission Definition) and B (Preliminary Design), in October 1997 (the start of government fiscal year, or FY, 1998). SIM expects to proceed into Phase B in FY2003 and then on to the Implementation phases (C, D and E) starting in FY2006. Phase C is the Detailed Design phase and Phase D is the Build and Test phase. Phase E is the Operations phase described above.

The NASA Office of Space Science ("Code S") has provided a cost cap for SIM's development phases B, C and D. This cap pre-supposes that NASA is able to maintain the funding profile agreed upon at the start of Phase B and so represents a significant commitment on the part of NASA. As such, detailed requirements have been worked out between the SIM project office and NASA headquarters that must be fully met prior to approval to enter phase B. So far, the SIM team is making excellent progress towards completing those requirements on schedule, leading to the expectation for an FY2003 entry into Phase B.

8. SUMMARY

This paper has briefly described the what, why and how of the SIM project, a key element of the National Aeronautics and Space Administration's (NASA) Origins theme and Navigator program. A wealth of additional information is available on all aspects of the SIM project via the SIM web site[8]. Significant details of various parts of the SIM mission are further described in several dozen other papers presented or posted during this conference[7].

7. ACKNOWLEDGMENTS

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8. Further information regarding all topics discussed in this paper can be obtained at the SIM web site at URL: http://sim.jpl.nasa.gov