National Aeronautics and Space Administration

SIM Lite

Astrometric Observatory

A Response to the Request for Information from Astro2010, the Astronomy and Astrophysics Decadal Survey Subcommittee on Programs

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

From Earth-Like Planets To Dark Matter

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Astronomy and Astrophysics Decadal Survey Subcommittee on Programs

SIM Lite Astrometric Observatory

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> "The results of Mercury's perihelion movement filled me with great satisfaction.
> How useful to us is astronomy's pedantic accuracy,
> which I used to secretly ridicule!"
>
> *A. Einstein in Einstein: His Life and Universe by Walter Isaacson (2007)*

Executive Summary

The SIM Lite Astrometric Observatory (SIM Lite) is a reduced-cost version of the astrometric mission called for in the 1990 Decadal Survey (Bahcall), in which NASA has invested 15 years and $590M to bring technology, mission design, and brassboard model hardware to a state where it is the only NASA astrophysics mission ready to proceed directly into Implementation (Phase C).

SIM Lite is a pointed observatory that will achieve unparalleled precision in astrometric measurements of stars from a visual magnitude of –1.5 to 20, and will produce seminal results in four key science themes and a General Observer program as summarized in the panel below and described in detail in Section 1.

Based on the results of independently peer-reviewed technology achievements at the component and system level, SIM Lite will achieve narrow-angle astrometry single measurements at 1 μas RMS 1-sigma, with the ability to achieve < 0.2 μas 5-year mission accuracy (multiple measurements). SIM Lite will achieve wide-angle astrometry at 4 μas RMS 1-sigma 5-year mission accuracy. The mission consists of a 6-m optical wavelength Michelson stellar interferometer with 50-cm apertures, described in Section 2.

No technology development remains. All technology was completed to Technology Readiness Level (TRL) 6 in 2005, and signed off by NASA HQ following independent review. Brassboard (form, fit, function) models of most instrument elements have been built and tested to required performance or better (see Section 3).

SIM Lite is in NASA Phase B, prepared to complete its Preliminary Design Review and move into implementation in less than a year, and could launch as early as 2015. Extensive investment in technology and risk reduction supports cost estimates that are at a high level of fidelity. Project cost estimates conducted in the Fall/Winter of 2008, presented in Section 6, involving multiple methods, produced an average estimate of development cost-to-go of $1,010M plus launch services in fiscal year 2009 dollars (FY09$). The operations cost range was $160M for 5.3 years of operations and one year of post-operations data archival. An independent estimate was conducted by the Aerospace Corporation under contract to NASA HQ, producing a multi-model–based estimate of $1,260M plus launch services for development cost-to-go and $150M for operations (FY09$).

SIM Lite Key Science Themes

The Search for Habitable Worlds — Earth-mass, habitable-zone planets orbiting nearby stars; planetary system architectures; birth and evolution of young stellar systems.

Dark Matter and the Assembly of Galaxies — Distribution of dark matter (DM) in the Milky Way (MW) and Local Group; role of DM in galaxy formation; masses of compact galactic objects with microlensing; rotational parallax–based luminosity-independent extragalactic distance measurement; formation history of the MW.

Precision Stellar Astrophysics — Physics of exceptional stars; compact-object astrophysics; Cepheid science and extragalactic distance scale.

Supermassive Black Holes and Quasars — What powers quasars? Inertial stellar reference frame science.

Charting the Uncharted Waters — New concepts; General Observer program.

Section 1. Key Science Goals

Summary

NASA's SIM Lite Astrometric Observatory (hereafter SIM Lite) will push the state of the art in astrometry by more than two orders of magnitude beyond what is possible today. The science of SIM Lite has been recognized and highly ranked by two previous Decadal Surveys. The 1990 Bahcall Report [1] laid out the case for stellar astrophysics and giant-planet discovery. During the intervening decade, huge strides in technology were made, allowing the 2000 Decadal (McKee &Taylor) Committee [2] to recommend a mission that could find not only giant planets but also rocky planets. SIM Lite is that mission.

SIM Lite will contribute in fundamental ways to a wide range of astrophysical problems. For planet searches, its precision is truly enabling and opens up a previously unreachable region of parameter space — a search of the nearest 60 or so nearest Sun-like stars for planets as small as one Earth mass orbiting in the habitable zone. It will map the distribution of dark matter in the Galaxy and the Local Group, trace the assembly of the Milky Way over cosmic time, and provide a critical test of Λ-CDM. It will provide a fundamental stellar reference frame, and study the physical processes revealed by motions of quasar jets.

SIM Lite represents the maturation of a development program that dates back to the original pre–Phase A studies for the Space Interferometry Mission (SIM) that began in 1996. SIM Lite represents a cost-effective approach to a precision astrometric instrument, obtained by judicious trading of the parameters that define the science: instrument performance, technical cost and risk, testability, and operational parameters like experiment design (e.g., target selection), observing strategy (cadence), and data analysis. The result is an instrument that retains virtually all the original science objectives of SIM, but with significantly reduced cost and risk.

Science Capabilities

SIM Lite is a pointed astrometric observatory that achieves global astrometry at 4 μas (microarcseconds) mission accuracy from V = –1.5 to 20; this greatly exceeds the capability of any other instrument, including the Gaia survey instrument, especially at the faint end. In its narrow-angle mode, it has 1 μas precision in ~1000 s and, with hundreds of repeated measurements over 5 years, a noise floor below 0.035 μas. This allows the detection of sub-Earth–mass planets around the closest stars.

Below we summarize the science of SIM Lite in four thematic areas. Detailed descriptions can be found in a comprehensive paper by Unwin et al. published in PASP [3], a series of Astro2010 White Papers (see references), and *SIM Lite Astrometric Observatory* — the SIM Lite Book [4] — a comprehensive study of the science case for SIM Lite.

Theme I. The Search for Habitable Worlds

SIM Lite will conduct a definitive search for Earth-mass planets in the habitable zone of nearby solar-type stars. It will have the ability to definitively search at least 60 stars. The mass of a planet is its most fundamental property — measured directly by SIM Lite. It will also determine orbits — are they nearly circular or are they too eccentric to lie fully within the habitable zone? SIM Lite will chart the full suite of planets from Earth-size rocky bodies through ice giants to gas giants, and it will provide extensive architectural details of planetary systems.

In this field, SIM Lite has no competition. It is fully capable of exploring the nearby stars for Earths — i.e., those stars within ~10 pc for which optical spectroscopy through direct imaging will eventually be feasible. Scientifically and technically, the path forward is clearly laid out in the 2008 Report of the Exoplanet Task Force [5] — a definitive astrometric search comes first, followed by a mission to do spectroscopy.

Fundamentally, there are two reasons for doing an astrometric survey first: (a) astrometry establishes existence, and because it measures mass, it is a foundation upon which to design and build a follow-up spectroscopy mission; and (b) SIM Lite is ready to proceed to PDR and the construction of the flight instrument.

Ground-based radial velocity (RV) observations have discovered over 300 exoplanets and are currently the major observational technique. But extending this technique to the regime of Earth-like planets in ~1 AU orbits for Sun-like stars is difficult because the signal is only ~10 cm/s. While sufficiently stable instruments can likely be built, starspots are likely to be a major limitation on the ultimate accuracy of RV. Starspots also affect astrometry, but much less [6,7]. Ultimately, both techniques have important roles in the field because of their differing sensitivity ranges (see Fig. 1-1), especially with a long time baseline (>10 years) of RV data.

In a separate program, SIM Lite will search for planets around young stars with a range of ages (2 to 100 Myr). This is a critical link in the chain of reasoning that defines our understanding of the formation and evolution of planetary systems into the mature systems that have been studied to date. This field is largely unexplored due to limitations on RV and imaging due to stellar photosphere activity, rapid rotation, and the gas and debris disks surrounding these objects. Simulations have shown that astrometry is much less affected [9].

Multiple-planet systems are an important research area for SIM Lite. It will provide masses and full 3-D orbits for planets in each system, including orbital inclinations and eccentricities, which are essential inputs to any study of the stability and evolution of multiple-planet systems: co-planarity is a convenient but unjustified assumption in current analyses. This multiple-planet capability has been verified through an extensive series of double-blind simulations [8] that were subjected to independent review by NASA, and in particular they confirmed the ability to detect Earths in the presence of other planets.

The legacy of the SIM Lite survey of at least 60 nearby stars will be:

• An inventory of those stars that have Earth-like planets orbiting in the habitable zone.

• Masses of these planets. Mass is a fundamental parameter for any planet. For low-mass planets orbiting at 1 AU or farther out, only astrometry has significant sensitivity (Fig. 1-1).

• Orbital parameters for those planets. Since planets can't "hide" from astrometry, this is important information that may be hard to derive well from images alone, and that will enhance throughput for future direct imaging missions.

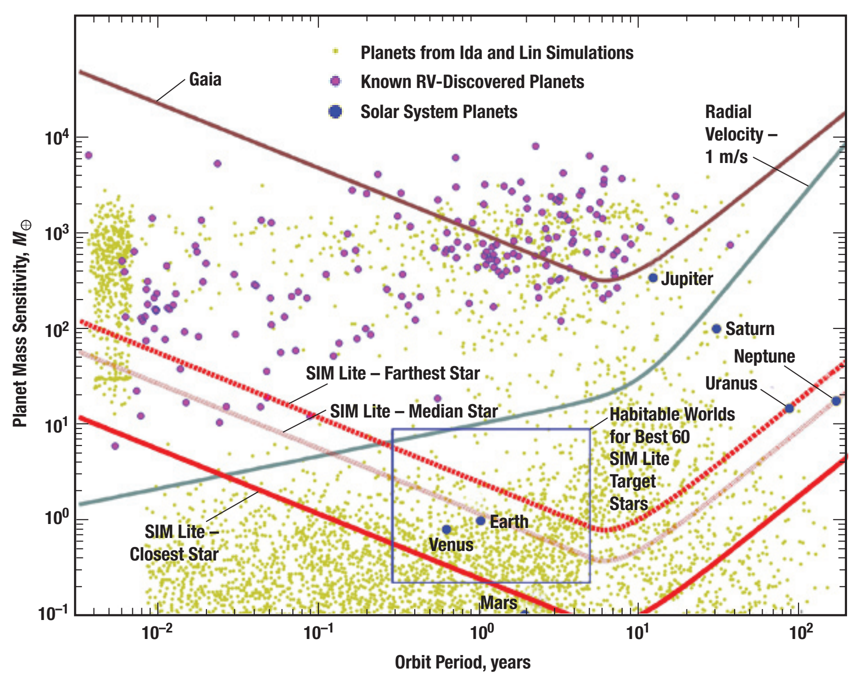


FIGURE 1–1. *The SIM Lite planet search space. The curves show the yield for an observing scenario in which each star is searched to the same astrometric signature; by varying the scenario, it is possible to search to a specified planet mass limit instead. The actual program will be optimized based on the state of knowledge of the field at launch. The limit of precision for RV is determined by astrophysical noise from starspots. Only 10% of stars are as quiet as the Sun, for which sunspots would limit RV precision to about 0.5 m/s.*

• A census of more massive planets out to a few AU; astrometry complements RV, which is more sensitive at very short orbit radii.

• For multiple-planet systems, orbital parameters needed for an understanding of the dynamics and system stability.

Direct detection (coronagraph) missions are a logical scientific follow-up. As well as an important scientific legacy, SIM Lite provides key inputs to the scope of a future imaging mission [9]:

• SIM Lite establishes existence. Kepler will establish statistics of exoplanets, generally at large distances, but SIM Lite will provide an actual list of nearby stars on which to invest time in follow-up imaging. The catalog from SIM Lite will provide a solid foundation upon which to scope the capabilities of a coronagraph for spectroscopy of exoplanets.

• A catalog of known planets would be a huge asset because it directs where a coronagraph mission should invest its observing time: you know the planet is there. That utility grows if Kepler finds that Earth-like planets are relatively rare.

• A coronagraph can operate efficiently on those stars for which a period is already known from SIM Lite, even without an accurate ephemeris (e.g., orbit phase). In many cases, the planets' orbits take them only just outside the inner working angle (IWA), and confirmation (which requires demonstration of a Keplerian orbit) is hard. Image-based orbit information will be difficult to obtain, but combining with SIM Lite data would rapidly provide very good orbital parameters.

• SIM Lite will likely find planets that lie within the IWA of a coronagraph. Those planets are unobservable by an imager, and only SIM Lite provides new knowledge of those systems.

• With unequivocal planet masses from SIM Lite, exoplanet spectra can be interpreted with more confidence. The mass, as a defining characteristic, sets the surface gravity (using planet cross-section estimated from imaging photometry), which in turn governs the retention of an atmosphere.

Scientifically, the path is clear. And as shown below, SIM Lite is ready technically, and can rapidly proceed to PDR and full development of the flight instrument.

Theme II. Dark Matter and the Assembly of Galaxies

Cold dark matter models and proposed alternatives offer testable predictions that make the Local Group and our own Milky Way key laboratories for exploring dark matter (DM) on these length scales. SIM Lite has a key role to play. Some of the most definitive tests of local DM require precision measurements of proper motions on distant faint stars moving under the influence of gravity from both luminous and dark matter — measurements that are uniquely the domain of SIM Lite. A survey mission such as Gaia cannot, in most cases, average enough stars at these faint magnitudes to achieve the necessary ensemble precision.

SIM Lite will constrain DM particle mass by measuring the motions of stars in Local Group dwarf spheroidal (dSph) galaxies. A cusp is indicative of cold and massive (CDM) particles, while a core is indicative of the warm light particles of "WDM." Radial velocities alone cannot resolve the problem.

SIM Lite will study the assembly of galaxies by measuring stellar motions in tidal streams around the Galaxy (Fig. 1-2). Streams trace the total mass distribution at all radii in the Galaxy. SIM Lite will also measure the motions of newly discovered ultra-faint satellite galaxies of the Milky Way. CDM predicts that these dSph galaxies fell into the Local Group recently, and as such, their motions should be different from those of older accretion events.

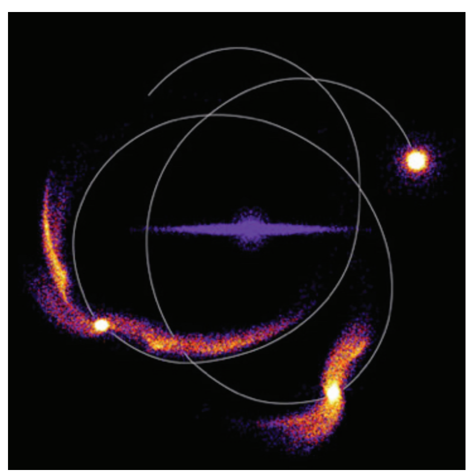


Figure 1–2. *Numerical simulation of the disruption of a dwarf spheroidal galaxy orbiting our Galaxy.*

Hypervelocity stars (Fig. 1-3) provide a means of measuring the shape of the total (dark matter) mass distribution of the Galaxy to large distances. With galactocentric velocities of >>600 km/s, these stars must have been ejected from close to a supermassive black hole at the center of the Galaxy.

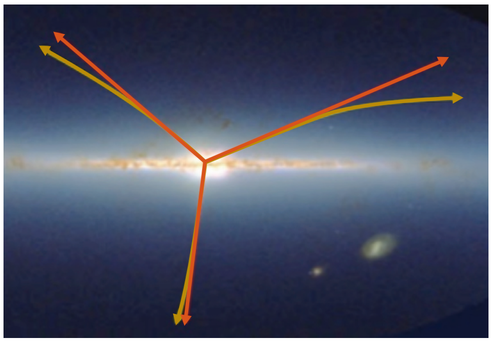


Figure 1–3. *Schematic representation of the trajectories of hypervelocity stars in a spherical (red) and non-spherical (yellow) potential.*

Theme III. Precision Stellar Astrophysics

SIM Lite will usher in a new era of precision stellar astrophysics. It will measure the masses of the largest and smallest main sequence stars, the masses of neutron stars and of stellar-remnant black holes. SIM Lite's reach across the Galaxy will provide precise distance measurements of rare objects. Statistical results from ensembles of stars, as derived from wide-area surveys such as Gaia, cannot be derived for rare objects. Raw precision, combined with the ability to go faint, is the critical attribute for SIM Lite experiments in stellar astrophysics.

SIM Lite will measure accurate distances (luminosities) to a significant number of the rare, massive O/B stars, supergiants, variable stars, and the central stars of planetary nebulae. It will measure accurate (1%) masses for the highest and lowest mass stars, to seriously challenge models of stellar structure. This sounds simple, but even today, such critical data are unobtainable. Black hole and neutron star binaries can test GR and extreme physical states. Many are in mass-transfer binary systems, for which SIM Lite can derive essential physical parameters: distances, binary orbit parameters, and masses of the compact objects.

Theme IV. Supermassive Black Holes and Quasars

Studying the details of the structures surrounding a supermassive black hole at the core of a galaxy requires a level of angular resolution that is presently reached only using very long baseline interferometry (VLBI) in the radio regime. SIM Lite's flexibly scheduled measurements will detect the apparent position shift due to activity in AGN. Proper motions of the brightness centroids are related to the origin of relativistic jets, corona, and accretion disk around the central supermassive black hole. It will measure the astrometric color shift, a vector quantity whose direction, orientation, and variability provide a handle on the relative contributions of different physical components.

Theme V: Charting the Uncharted Waters

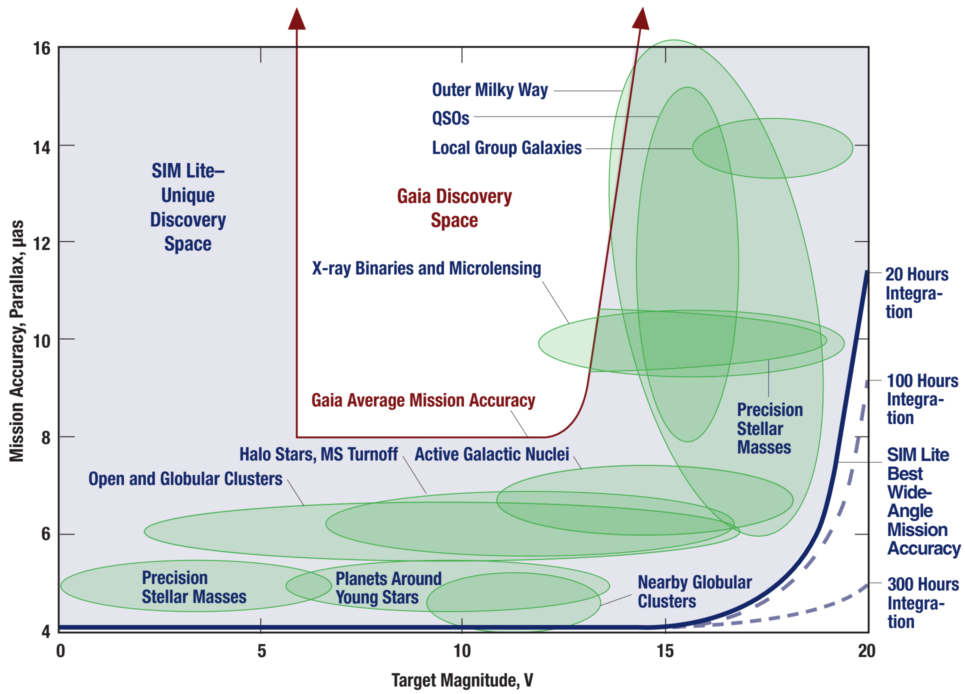
As an astrometric observatory, SIM Lite will have a substantial General Observer (GO) program [4] allocating approximately half the science time, and enabling researchers in the astronomy community to reap the benefits of precision astrometry. SIM Lite is a pointed mission with more in common with observatories like HST and Spitzer than survey missions such as Gaia.

What new science is there for SIM Lite to do beyond the Science Team's programs? In April 2008, the SIM Lite Project and NASA Exoplanet Science Institute (NExScI) issued a proposal call for studies to find an answer to exactly this question. The result was the peer-reviewed selection of 19 one-year studies, spanning a wide range of science topics including truly novel experiments that SIM Lite could perform (Chapter 13 of [4]).

A Note on SIM Lite and Gaia

SIM Lite and Gaia are truly complementary. The Gaia survey (Fig. 1-4) will be a powerful engine for Galactic astrophysics, using large statistical samples. SIM Lite does high-precision experiments on small numbers of objects tailored to specific science objectives. Some, like the Galactic structure experiments described above, are examples that can only be done by SIM Lite.

Figure 1–4. *Parameter space for wide-angle astrometry with SIM Lite and Gaia. We show only the experiments planned for SIM Lite (ovals). Gaia has planned a large number of experiments that occupy the middle (unshaded) area. Conclusion: this parameter space defines a broad range of experiments that overlap very little between the capabilities of Gaia and SIM Lite. SIM Lite has the additional capability of astrometry to 0.035 μas (end of mission) over a narrow field on bright targets (for exoplanet searches).*



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Astro2010 Science Frontiers Panels — White Papers

http://www7.nationalacademies.org/bpa/Astro2010_SWP_byTitle.html
[10] Beichman, C. A., Formation and Evolution of Planetary Systems, #15.
[11] Benedict, G. F., Astrometry — Challenging our Understanding of Stellar Structure and Evolution, #17.
[12] Gould, A., Mass Spectrum of the Galaxy, #101.
[13] Johnston, K. J., Is There a Need for an Improved Celestial Reference Frame?, #143.
[14] Kasting, J., Exoplanet Characterization and the Search for Life, #151.
[15] Kulkarni, S. R., No Planet Left Behind: Investigating Planetary Architecture and Diversity with SIM Lite, #178.
[16] Olling, R., An Era of Precision Astrophysics: Connecting Stars, Galaxies and the Universe, #226.
[17] Shao, M., Astrometric Detection of Planets, #271.
[18] Shao, M., Direct Detection and Spectroscopy of Exo-Earths; The Need for High Angular Resolution and Other Observational Requirements, #272.
[19] Shaya, E., Properties of Dark Matter Revealed by Astrometric Measurements of the Milky Way and Local Galaxies, #274.
[20] Tomsick, J., Optical Astrometry of Accreting Black Holes and Neutron Stars: Scientific Opportunities, #297.
[21] Wehrle, A., What is the Structure of Relativistic Jets in AGN on Scales of Light Days? #310.
[22] Worthey, G., Extragalactic Stellar Populations, #325.

Section 2. Technical Overview

The SIM Lite flight system (Fig. 2-1), consisting of a spacecraft and a single large optical instrument, will be launched into the same Earth-trailing solar orbit (ETSO) as were Spitzer and Kepler by an intermediate-class Evolved Expendable Launch Vehicle. The 2,930 kg current best estimate (3,760 kg including mass contingency) of the SIM Lite wet mass results in a launch vehicle mass margin of 36%. In the ETSO, the flight system will receive continuous solar illumination, maintaining a stable thermal state and avoiding the occultations that would occur in an Earth orbit. SIM Lite will slowly drift away from the Earth at a rate of slightly more than 0.1 AU per year, reaching a maximum communication distance of about 0.6 AU after 5.4 years.

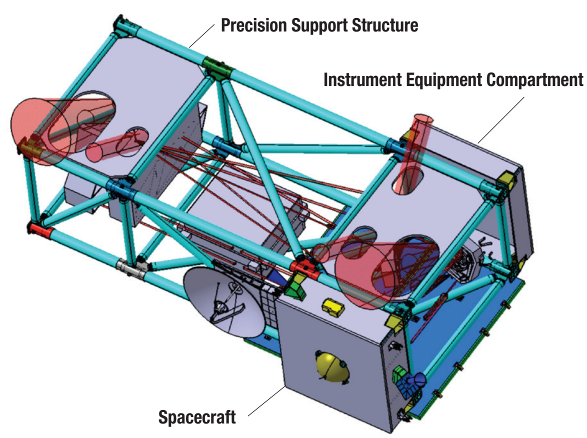


Figure 2–1. *The SIM Lite flight system consists of a spacecraft and a single large optical instrument. The instrument components are mounted on the precision support structure, which functions as a highly stable optical bench.*

The SIM Lite instrument makes sequential angular measurements of the positions of stars projected along the interferometer baseline. All astrometric signals are two-dimensional on the sky, so every science measurement requires, at some later time, a repeated measurement with the baseline oriented approximately orthogonal to that of the first measurement. Individual stars are observed within "tiles" and the complete set of data on a given star will normally comprise many tens or hundreds of tiles. Observations of different stars are integrated at the level of tiles (from one to dozens of stars per tile) and then onto campaigns of tiles.

An observing campaign on a specific target comprises the set of tiles that include that object. Depending on the science objective, these may be organized into "narrow-angle," "grid," or "wide-angle" campaigns. An individual tile may be as short as 10 minutes, or as long as a couple of hours. The science siderostats provide a field of regard that is 15 degrees in diameter, centered on the Guide-1 interferometer boresight. Any target within 7.5 degrees of the center may be included in a tile.

Because SIM Lite can observe stars no farther apart than 15 degrees with a single spacecraft pointing, the measurement of wider angles involves the overlapping of tiles, with at least two "grid" stars in the overlap region. The "grid" is a set of 1302 overlapping tiles that cover the entire sky. Stars specifically chosen for the purpose of defining a wide-angle reference frame are termed "grid stars." There are typically 6 to 7 grid stars per tile. The SIM Lite Project, after extensive simulation studies, selected galactic K-giant stars with a median magnitude V = 10.0 and median distance 700 pc for the grid.

Observations of "wide-angle" targets are built upon the framework defined by the astrometric grid. Virtually all observations of wide-angle astrometry targets can be achieved by inserting those targets into grid tiles. Since all data within a tile are referred to the same inertial science instrument baseline, the astrometric parameters extracted from the data set of wide-angle data are automatically referred to the grid. This is exactly what is needed for measurements of parallax and proper motion, for which the reference frame must be quasi-inertial.

The narrow-angle (NA) observing scenario is used for the astrometric search for exoplanets and other investigations requiring the utmost performance of SIM Lite. In this scenario, a target star's motion is measured across many visits against a set of reference stars located in a 2-degree-diameter field. As noted, the experiment design and instrument design are tightly coupled. In this case, the extreme astrometric accuracy is enabled by two design factors: (1) rapid switching between target and reference stars effectively eliminates errors caused by long-term (e.g., thermal) drifts since the relevant timescale for the instrument thermal stability is reduced to ~90 s; and (2) differential measurement over small angles, and shared over several targets, eliminates a number of field-dependent errors that would be present in the wide-angle scenario. The reference stars are chosen to be astrometrically well described by position, proper motion, and parallax. The basic NA measurement is the delay difference between the target and a reference star, and the analysis uses these measurements pair-wise.

Science Planning and Operations

SIM Lite will observe two kinds of science programs — those of the NASA-selected SIM Science Team, and those selected through General Observer proposal call shortly before launch, and administered by the NASA Exoplanet Science Institute (NExScI). Observations will be preplanned before launch, paying particular attention to the cadence of observation to optimize the science objective. NExScI will provide planning and performance estimation tools for this purpose. NExScI will prepare a 5-year schedule by fitting observation requests, spacecraft maintenance, data downlinks, calibrations, and other flight activities into the timeline. NExScI will also perform the science data reduction and archiving [2].

SIM Lite Instrument Overview

The SIM Lite single optical instrument (Fig. 2-2) consists of four fundamental optical sensors: the Science Michelson stellar interferometer, the Guide-1 Michelson stellar interferometer, the Guide-2 high-accuracy star-tracking telescope, and the external metrology, all mounted on a precision support structure (PSS), which functions as a highly stable optical bench. The science interferometer makes sequential astrometric measurements of the positions of stars that can be processed to represent angles on the sky projected along the interferometer baseline. Both during and between measurements, the science interferometer baseline orientation in inertial space is monitored by continuous observations of known, bright stars (referred to as "guide" stars) with the guide interferometer and telescope. The Guide-1 interferometer measures the instrument attitude to better than 1 μas in the science interferometer measuring direction by tracking a guide star in the same direction as the science target. The Guide-2 telescope measures the attitude to 50 μas in the other two directions by tracking a second guide star, roughly 90 degrees away from the first one. The science interferometer can be regarded as inertially fixed, to a precision better than the individual measurements, during and between science measurements. The two guide sensors also provide real-time corrections to the pointing of the science interferometer when observing faint target stars. The Guide-1 interferometer baseline and the Guide-2 telescope line of sight are optically tied to the science interferometer by the external metrology truss system. A detailed description of the instrument and how it is used to make astrometric observations can be found in Ref. [1].

The science interferometer collects light from two 50-cm siderostats separated by the 6-meter baseline. The siderostats articulate over an angular range of +3.75 degrees, giving the science interferometer a 15-degree-diameter field of regard (FOR). Once they are pointed at a star, these actuators are locked in place for the duration of the observation. In the optical train beyond the siderostat, each beam is compressed to a diameter of 4 cm using a confocal beam compressor. Next in the path is the fine steering mirror (FSM), which, compared to the siderostat, has a smaller range of motion but a much higher pointing resolution. It is used to track the star as the instrument attitude changes. The pathlength optic mechanism (POM) then folds the beam into the delay lines. The POM scans and stabilizes the starlight fringe by applying fine and relatively small delay modulations. Both the FSM and the POM are momentum-compensated so as not to

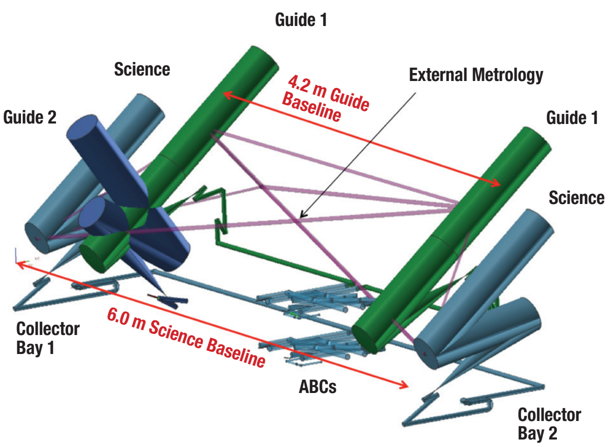


Figure 2–2. *The SIM Lite optical instrument consists of four optical sensors: (1) the science Michelson stellar interferometer, (2) the Guide-1 Michelson stellar interferometer, (3) the Guide-2 high-accuracy star-tracking telescope, (4) and the external metrology system. These are mounted on the PSS, a highly stable optical bench (not shown). A detailed description of the instrument can be found in Ref. [1].*

disturb the interferometer while observing. The delay line provides the coarse correction to the optical path difference between the two arms, with a 40 cm mechanical range. With two such delay lines in one of the two collectors, a total optical path difference of 160 cm can be produced between the two sides, enabling interferometry within the 15 degrees FOR. The delay lines only move during retargeting to a new science object and are then locked into place. The other collector has static delay lines to keep the optical design symmetry in the two arms of the interferometer. Finally, the beam is folded towards the center of the instrument where the two sides are combined to form fringes inside the astrometric beam combiner (ABC). The ABC contains the compensated combiner optics that re-combines the light coming from the two collectors and forms interference fringes, the angle tracker camera that monitors tip-tilt for pointing control of the FSM, the internal metrology sensor that tracks the internal propagation pathlength from the siderostat to the combiner optics and the fringe tracker camera that integrates the interference fringes.

The design for the Guide-1 interferometer is similar to the science interferometer, with a few simplifications. First, because the spacecraft points the entire instrument to the Guide-1 star each time, there is no need for Guide-1 siderostats and delay lines. Hence, the first Guide-1 optic is the primary mirror of the confocal compressor. Second, the Guide-1 star is selected to be brighter than visual magnitude 7, so a 30 cm Guide-1 collecting aperture is adequate. The optical compressor reduces the beam size by a factor of 7.5 so that the downstream optics have the same clear aperture of 4 cm as the science interferometer. Due to packaging constraints, the Guide-1 baseline is reduced to 4.2 m. Finally, in Guide-1 the optical delay line is corrected using a single mirror on a coarse motor stage, since only 1 mm of travel is needed.

The Guide-2 telescope monitors the roll of the spacecraft about the vector pointing to the Guide-1 star. This roll is primarily caused by the drift of the attitude control system (ACS). Guide-2 has a siderostat similar to the science siderostat, with a smaller aperture (30 cm instead of 50 cm) and a smaller 2-degree range, but with two stages of actuation to provide the higher pointing resolution required to track the star while the ACS is drifting. The siderostat coarse stage acquires the guide star and then locks, just as in the science siderostat. Then, the fine stage takes over the role of the FSM in the interferometers. The approach results in fewer reflections and easier fit on the optical bench.

The external metrology is needed to monitor the relative positions of SIM Lite's fiducials, four of which define the science and guide interferometer baselines. The measurements are made using heterodyne metrology beam launchers using the same principles employed in internal metrology. However, rather than measure the path difference between the left and right arms of the interferometers, the external metrology beam launchers monitor the direct distance between each pair of fiducials. Nine beam launchers are used to monitor the external metrology truss, which has five fiducials.

The PSS is a highly stable structure accommodating the instrument components. It is the primary load-carrying member of the SIM Lite flight system, and interfaces directly to the launch vehicle adapter. Beyond supporting the instrument subsystems, it maintains the thermal environment and provides solar shield and contamination protection. The PSS is a tubular truss-structure built up from carbon fiber reinforced plastic longerons and custom-designed titanium joint fittings.

The instrument real-time control system uses a Rad750-based computer located in the instrument equipment compartment, attached to the side of the PSS. Feedback control loops between the sensors located in the ABC and the actuators located in the collector bays, are implemented in C++ and are run at a few hundred hertz. The control electronics are distributed along the PSS to limit cabling length. The equipment compartment also hosts the laser metrology source for the internal and external metrology systems.

SIM Lite Spacecraft

The SIM Lite spacecraft is a three-axis stabilized, zero-momentum platform. Using Northrop Grumman heritage components and software, it provides the standard spacecraft functions of attitude control, electrical power, thermal control, data management, telecommunications, and software. The graphite honeycomb spacecraft structure is shaped like an open bookshelf. It houses the propellant tank in the center with all the other components mounted on its faces. The open side faces the PSS and is thermally isolated from it with multilayer insulation. The ACS provides space vehicle maneuvering to position the instrument to 3 arcsecond, 1-sigma, and stability of 0.2 arcsecond/100 seconds to support the science mission. Its four Teldix reaction wheels and inertial reference unit (IRU) have flight heritage, and its Galileo star trackers will be flying on the Lunar Crater Observation and Sensing Satellite. Momentum unloading is achieved via four Northrop Grumman dual-thruster monopropellant modules. The thrusters are oriented and operated such that no delta-V is imparted during momentum wheel desaturation. Two-stage vibration isolation on the reaction wheels reduces jitter to the levels required by the interferometer.

The redundant command and data handling subsystem uses a Rad750 processor board with 36 MB of RAM manufactured to host the flight software and control the spacecraft. A 96 Gbit (single side) onboard data storage system is almost twice the required 50 Gbit/week memory for science data.

Communication is by X-band low-gain omnidirectional antennas for both uplink and downlink for command and telemetry. Science data are downlinked using the Ka-band high-gain body-mounted non-articulated antenna. Doppler ranging will be performed via the X-band uplink/downlink or X-band uplink/Ka-band downlink. Differential one-way (DOR) ranging is also supported via X-band or Ka-band.

Spacecraft power is provided via a single-wing, dual-gimbaled, triple-junction GaAs solar array and Saft lithium batteries. The 96 Ahr battery's main function is to provide power during launch and from launch vehicle separation to solar array deployment with some limited capability during safe modes. During normal operations, the 4400 W (end of life) solar array provides all onboard power. The end-of-life capability of the power system includes a 30% contingency on the current best estimate of the instrument power.

SIM Lite Operation

Following orbit insertion, the spacecraft systems will be checked and tracking data collected to precisely determine the actual orbit achieved. Verification and calibration of the spacecraft and instrument will be performed during this in-orbit checkout (IOC)/science verification period, lasting about 4 months. Following this period, the SIM Lite instrument will operate for 5 years, performing nearly continuous science observations over the entire celestial sphere. Separate interleaved wide-angle and narrow-angle campaigns occur throughout the mission.

Pointing of the flight system will be performed using reaction wheels, with small reaction control system thrusters used for desaturation. Pointing will be performed such that the viewing axis will never be within 45 degrees of the Sun to protect the viewing optics from heating. The flight system's velocity is required to be determined to an accuracy of 20 cm/sec or better for stellar aberration correction and the position to better than 50 km for parallax correction. This will be achieved using ranging and Doppler data obtained during two 8-hour tracking passes per week using DSN 34-m ground stations. Science and engineering data will be recorded onboard and downloaded during the same tracking sessions. Frequency and duration of the Ka-band high-gain antenna science data downlink sessions will be no more than 8 hours per week (end of mission).

SIM Technical Overview Summary

SIM Lite is the result of over 13 years of design evolution that has resulted in a simpler and more robust mission and system design that still achieves all the science envisioned by the Astrometric Interferometry Mission (AIM), originally recommended by the 1990 Astronomy and Astrophysics Decadal Survey.

References

[1] Davidson, J.M., (editor), 2009, *SIM Lite Astrometric Observatory: From Earth-Like Planets to Dark Matter*, NASA, JPL 400-1360, Theme VI, Sections 16 through 20.
[2] Astrometric performance, operations, and planning reference papers on the SIM Lite website at URL: http://planetquest.jpl.nasa.gov/SIM/keyPubPapers/simBibliography/index.cfm?Cat=8

Section 3. Technology Drivers

The SIM Lite architecture is enabled by the exceptional performance of the full SIM mission system (40% better than NRC Decadal "Goal" levels) that resulted from the stunningly successful SIM technology development program. The SIM Lite architecture uses only technology already developed and demonstrated for SIM at the time of its technology program completion in July 2005 and uses hardware designs demonstrated during SIM's engineering risk reduction program where a series of brassboards (form, fit, function to flight) were (or are being) built and subjected to environmental, performance, and life tests. There are no additional technology elements remaining to be developed for SIM Lite (Fig. 3-1). The Aerospace Corporation, in conjunction with the NASA Headquarters–chartered SIM Lite independent cost estimate (October 2008 through January 2009), also performed an independent technical assessment. Their assessment was that "Most technologies [are] at TRL 6 or [are] anticipated to be by the end of FY09. Progress is appropriate for this stage of the project." The following material briefly reviews the SIM technology development history. For a more detailed discussion, see Refs. [1], [2], and [3].

SIM Technology Development Program

The SIM technology program begun in 1994 was geared toward demonstrating 1 μas astrometric precision, with a systematic error floor below 0.2 μas needed to support planned narrow-angle science. The program verified component, subsystem, and system-level technologies in both real-time nanometer fringe control and in picometer optical element position and fringe measurement. The technology program had three parts: (1) detailed error budgets; (2) physical models (testbeds), and

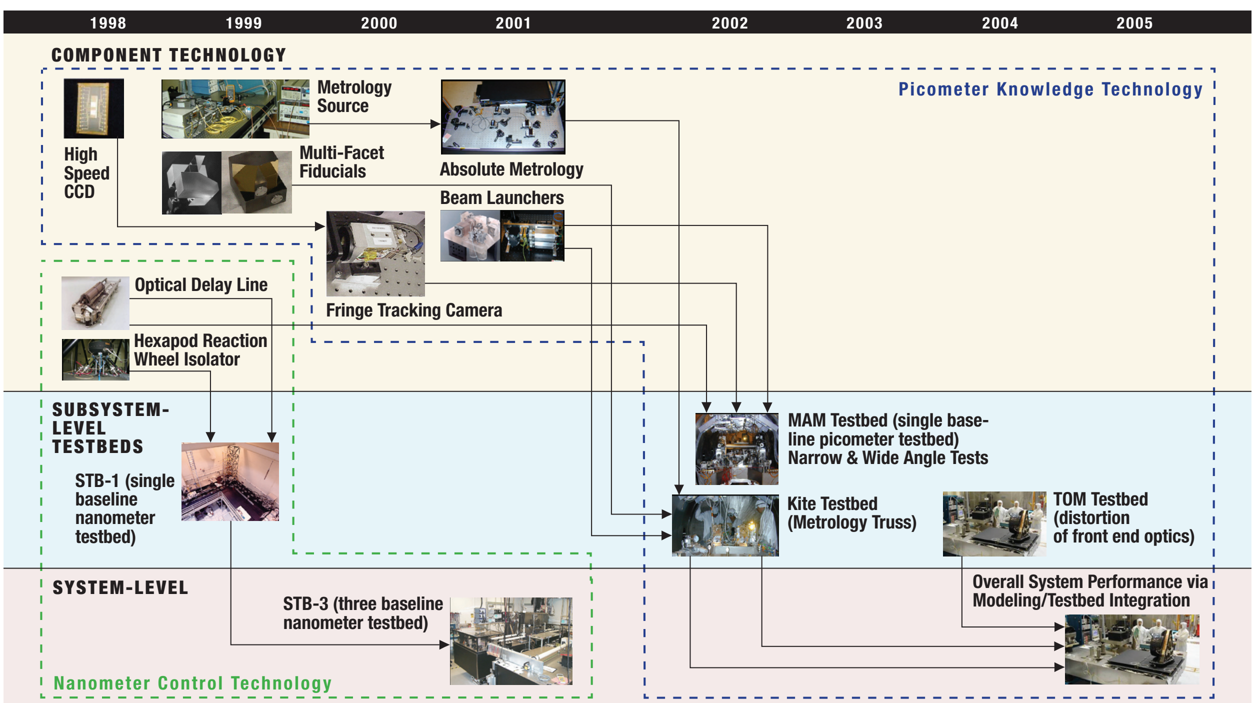


Figure 3–1. *The SIM Lite technology development program has developed all major technology elements to TRL 6 and therefore to readiness for PDR. Detailed descriptions of the SIM Lite Technology Development Program can be found in Refs. [1], [2], and [3].*

(3) detailed numerical models that were required to agree with the physical model (testbed) results within a factor of two. The last system-level activity demonstrated how the instrument picometer knowledge performance verification and validation (V&V) would be accomplished during flight integration and test.

This technology program was so successful that it demonstrated that the full SIM would achieve performance 40% better than the Goal-level performance envisioned by previous Astrophysics Decadal surveys. It was this over-achievement in performance that enabled the simplifications needed for SIM Lite.

Engineering Risk Reduction Activities

With the completion of the technology program, SIM transitioned into reducing engineering risk. Flight-qualifiable brassboard (BB) versions of the key hardware elements were or are being built that achieve form, fit, and function to the flight designs. Fig. 3-2 shows an overview of the brassboard hardware, and how the pieces form the SIM Lite Instrument.

Note that the only three remaining assemblies, shown as CAD models in the figure, are currently under construction (and will be completed and tested before the Fall of 2010). The BB modulating optical mechanism (MOM) is being assembled

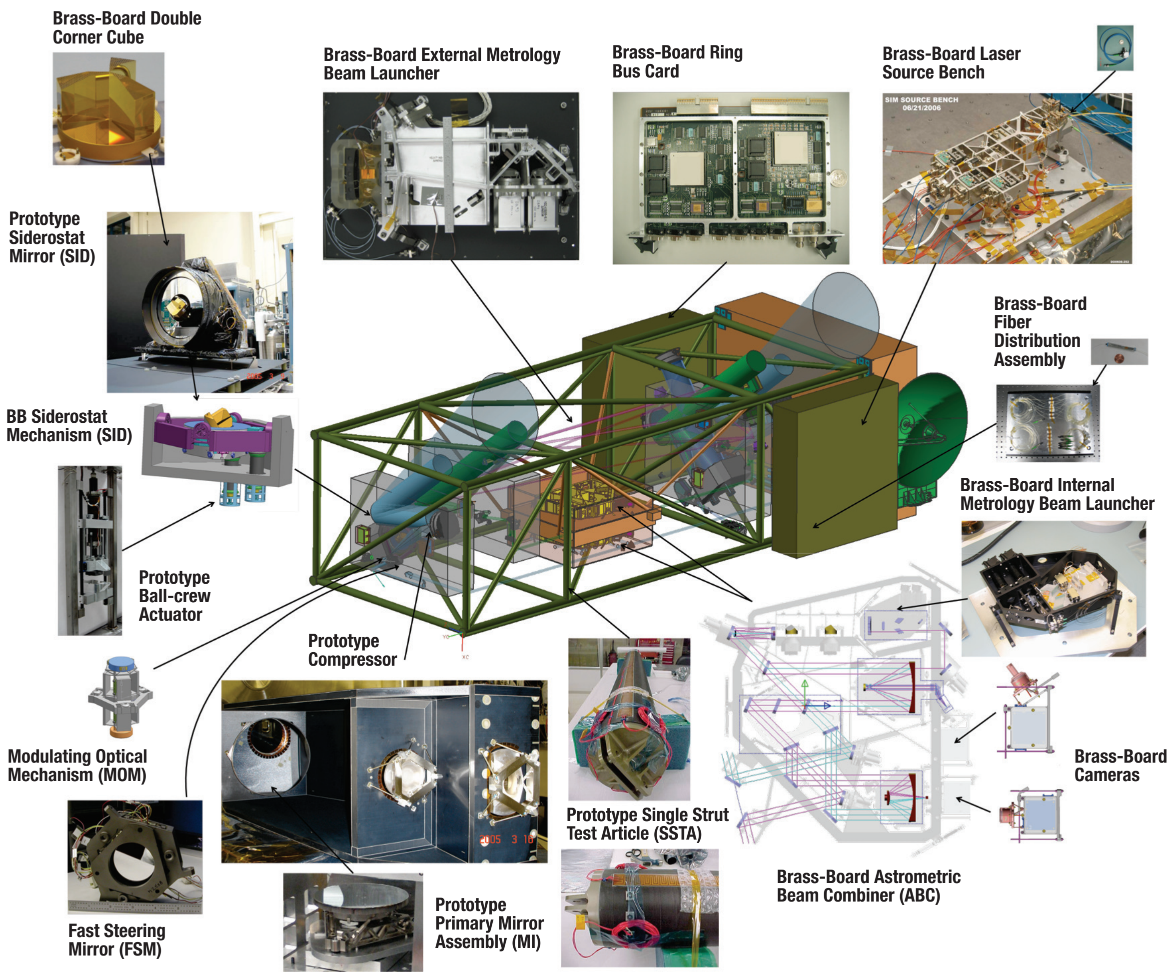


Figure 3–2. *SIM Lite brassboard hardware that makes up the instrument.*

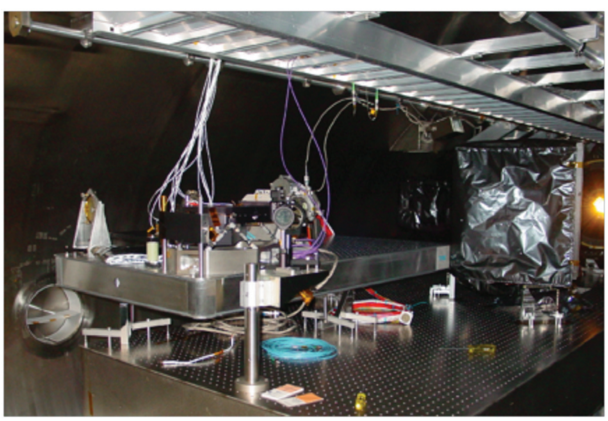
and will be tested in May 2009, the BB astrometric beam combiner (ABC) is slated to finish by the end of 2009, and the BB siderostat by mid-2010. SIM's ongoing development of hardware assemblies into flight-like assemblies continues to show that JPL's standard flight hardware development processes are 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 Lite mission. Further information about this technology program can be found in the references for this section.

Guide-2 Star Tracker

One of the most significant differences between the SIM and SIM Lite designs, other than scaling, is the replacement of the Guide-2 Michelson Stellar interferometer with an ultra-stable star-tracking telescope (100,000 times more accurate than a typical spacecraft star tracker), called the Guide-2 telescope (Fig. 3-3). This telescope uses only components that were already developed for SIM. Because of that, we were able to re-use equipment from other testbeds and, in 18 months, develop and demonstrate the needed stability requirement. The performance of 50 µas was achieved in February 2009, and a close-out review is scheduled for April 2009.

Technology Readiness Summary

SIM Lite has demonstrated all the technology and engineering needed for flight by leveraging on the investment in SIM's technology development program. The current funding will complete the entire suite of brassboard hardware, such that every SIM Lite component will have been vetted for manufacturing, technology, and performance risks prior to the end of FY2010. SIM Lite is technically ready for full-scale development.



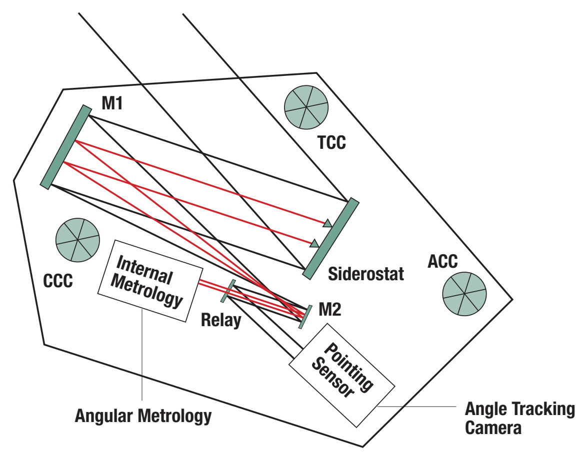


Figure 3–3. *The Guide-2 telescope testbed in the vacuum chamber (left). This testbed has demonstrated star-tracking capability at an unprecedented 30 µas level. Diagram of the Guide-2 telescope (right).*

References

[1] Davidson, J. M., (editor), 2009, *SIM Lite Astrometric Observatory: From Earth-Like Planets to Dark Matter*, NASA, JPL 400-1360, Theme VI, Section 19.
[2] Marr, J. C., "SIM Technology White Paper for the Exoplanets Task Force," Jet Propulsion Laboratory, California Institute of Technology, on the SIM Lite public website at URL: http://planetquest.jpl.nasa.gov/documents/TechExoPTF_Final.pdf
[3] Laskin, R. A., 2006, "Successful Completion of SIM PlanetQuest Technology," proc. SPIE 6268, 626923; also on the SIM Lite public website at URL: http://planetquest.jpl.nasa.gov/documents/SPIE_06-rev6_small.pdf

Section 4. Activity Organization, Partnerships and Current Status

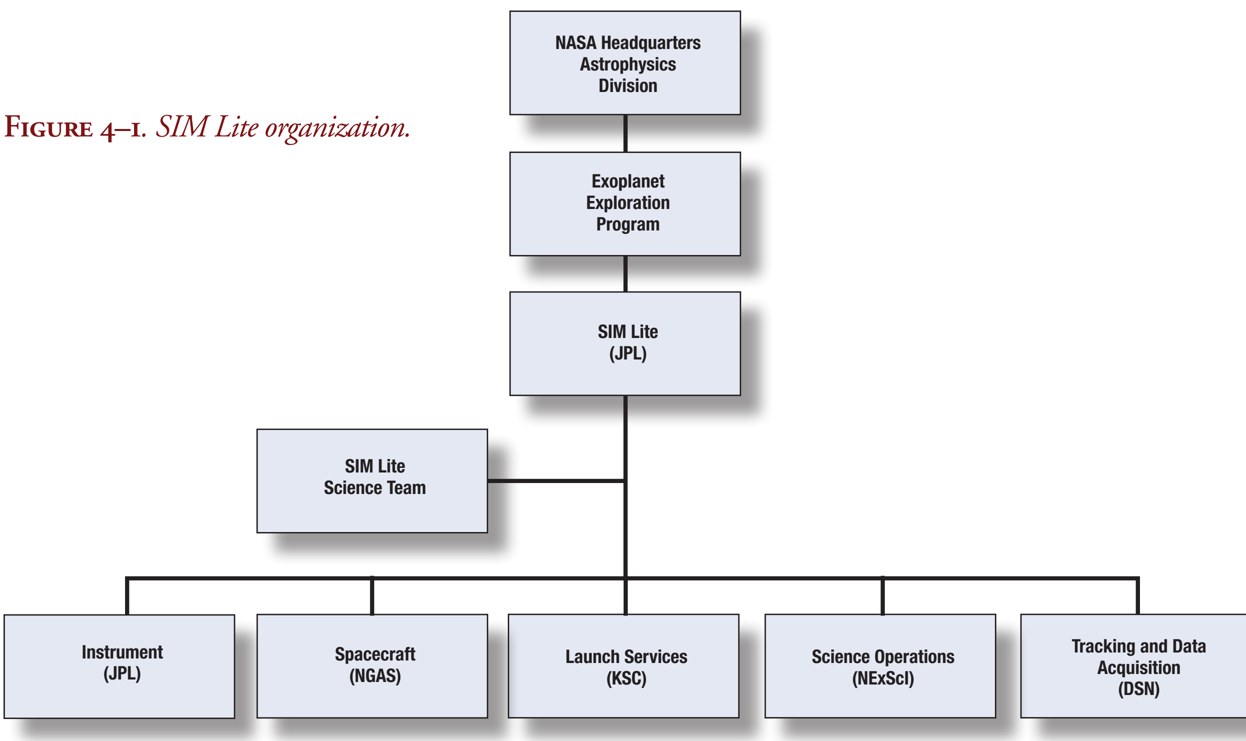
SIM Lite is a large-class mission funded by NASA as part of the Exoplanet Exploration Program. It is currently in late Formulation Phase (Phase B) conducting engineering risk reduction activities, building and qualifying brass board model hardware.

The SIM Lite organization (Fig. 4-1) brings to bear the strengths of a competitively selected science team to define the science investigations and the technical performance drivers, the Jet Propulsion Laboratory (JPL) to manage the project, develop and validate the technology, design and build the instrument, and conduct mission operations, and Northrop Grumman Aerospace Systems (NGAS) to provide the spacecraft and the precision support structure for the instrument. NASA Kennedy Space Center provides launch services, and the Deep Space Network provides tracking and data acquisition. NExScI, part of the Astrophysics Data Centers at Caltech, provides science operations, data archival, and analysis tools. The core team has been in place since project inception in 1997.

The Science Team selected through the first AO consists of 10 Key Science PIs and 5 Mission Scientists. Together with their Co-I teams, approximately 70 scientists are involved. Approximately one-half of the science observing time of the mission has been assigned to this team.

Yet to be selected, General Observers will be solicited through future AOs and the remaining half of the science time assigned to their observations. As discussed in Section 2, a solicitation for science studies to test the "Uncharted Waters" of new investigations using the unique capability of SIM Lite resulted in the selection of 19 novel new ideas for science investigations.

Figure 4–1. *SIM Lite organization.*



Section 5. Activity Schedule

SIM Lite is built on the past Formulation Phase history for the SIM mission that began with Phase A start in October 1997 and Phase B start in July 2003. All the technology work was completed by July 2005 and significant additional engineering risk reduction has occurred since then, as described in the technology section. Because of this precursor work, we have high confidence in the fidelity of the estimated cost and schedule to go.

The most recent independent cost estimate (ICE) for SIM Lite was performed between October and January 2009 by the Aerospace Corporation [1]. At the same time, a JPL institutional cost estimate was developed using multiple models. Both used a very detailed version of the optimum SIM Lite schedule (outlined below) that was delivered with the detailed Cost Analysis Data Requirements (CADRe) developed to support the independent cost estimates.

The optimum schedule for the development of SIM Lite assumes an October 2010 start, launch in July 2015, 30-day post-launch IOC (part of Phase D), 120-day science calibration, 5 years of operations, and 1 year of post operations final data processing, archival, and project closeout. Table 5-1 shows the significant project milestones, their dates, and the years from the start of FY2011.

Table 5-1. *Schedule.*

Event	Date for a July 2015 Launch	Years from start of FY2011
Start development for launch	*October 2010*	*0*
Mission-level PDR	*October 2011*	*1.0*
Implementation Phase C/D start	*January 2012*	*1.3*
Mission-level CDR	*October 2012*	*2.0*
Observatory I&T (Phase D) start	*June 2014*	*3.7*
Launch Readiness Date (LRD)	*July 2015*	*4.7*
IOC complete; operations (Phase E) start	*August 2015*	*4.8*
Science calibration complete	*December 2015*	*5.3*
5-year science ops complete	*December 2020*	*10.2*
Post-Ops activities complete (Phase F)	*December 2021*	*11.2*

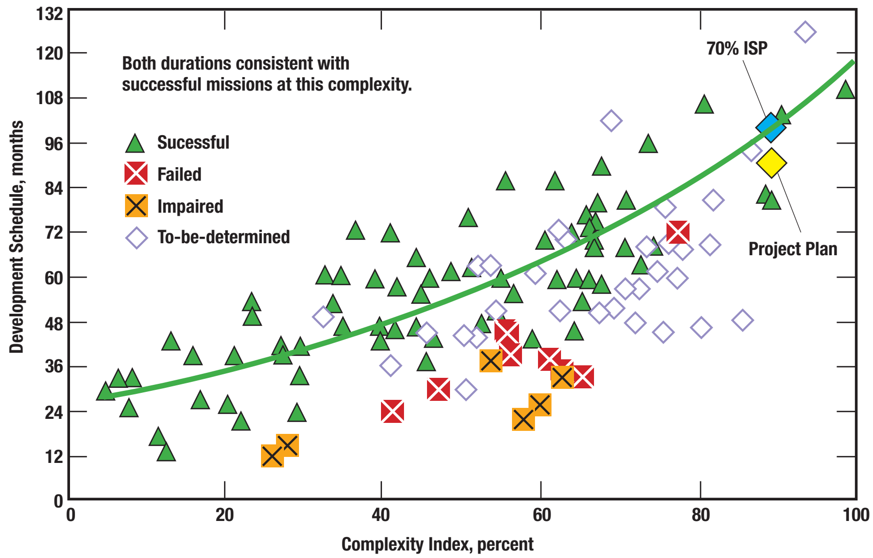


Figure 5–1. *SIM Lite schedule estimate. This figure compares the SIM Lite estimated schedule with those of other missions of varying complexity. The plot shows that both the JPL and 70% Aerospace schedules are consistent with successful missions of similar complexity.*

Schedule Validation

As part of the Aerospace ICE, an Independent Schedule Estimate and a complexity-based risk assessment (CoBRA) [2] were performed. This tool uses up to 40 parameters to describe the mission and computes a complexity index relative to other missions in the Aerospace CoBRA database. The SIM Lite complexity index and schedule estimates are then plotted relative to ~110 other missions in the database (see Fig. 5-1).

The points in this plot are: Green-diamond = successful; Yellow-X = impaired; Red-X = failed; gray-diamond = yet to be determined.

The plot shows that both the JPL and 70% Aerospace schedules are consistent with successful missions of similar complexity.

References

[1] The Aerospace Corporation, "SIM Lite Independent Cost, Schedule, and Technical Readiness Evaluation Assessment," NASA HQ Briefing, January 27, 2009.

[2] David A. Bearden, "A Complexity-Based Risk Assessment of Low-Cost Planetary Missions: When Is a Mission Too Fast and Too Cheap?," Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, May 2–5, 2000.

NASA Mission Life Cycle Phase Definitions

Phase A = Concept and Technology Development
Phase B = Preliminary Design and Technology Completion (including long-lead procurements)
Phase C = Final Design and Fabrication
Phase D = System Assembly, Integration, and Test (I&T), and Launch
Phase E = Mission and Science Operations and Sustainment
Phase F = Closeout

Section 6. Cost Estimate

SIM Lite is a lower-cost derivative of the deeply studied SIM design. It capitalizes on all the astrometric instrument technology development, design, and engineering risk reduction activities undertaken over those years for the SIM mission (12.5 years and $590M RY$ invested to date). Having built and tested brassboards (form, fit, function) of most of the critical hardware assemblies for SIM Lite under the prior SIM funding, the fidelity of the SIM Lite cost estimate provided here is very high.

SIM Lite Cost Estimate Methodology

The estimate provided in this section is the life cycle cost-to-go in fixed government Fiscal-Year 2009 dollars (FY09$).

The most recent independent cost estimate (ICE) for SIM Lite was performed between October and January 2009 by Aerospace Corporation under contract to NASA Headquarters [1]. At the same time, a JPL institutional cost estimate was developed. A very detailed Cost Analysis Data Requirements (CADRe) document, which provides detailed data defining the mission to be developed, was prepared by the SIM Lite Project in October 2008 and used as input to a broad suite of cost estimating methods at both Aerospace and JPL.

JPL estimating methods used included a Project grass roots estimate; a JPL Team X estimate; and an array of estimates from JPL's Engineering Cost Estimating Office, using the SEER, PRICE, PMCM, and Analogy methods. The Aerospace Corporation, using the same CADRe, also used a broad array of estimating methods, including SEER, PRICE, MICM, Analogy, USCM8, and NAFCOM 2006.

The JPL institutional estimate resulted from averaging the several separate JPL estimates. Similarly, the Aerospace ICE estimate was derived as an average of the several Aerospace estimates. Both estimates were completed and presented to NASA Headquarters on January 27, 2009.

All these estimates were performed using a much more detailed version of the schedule described in the previous section, namely, an October 2010 development start date with launch in July 2015, followed by one month of IOC (included in Phase D), 4 months of calibration, 5 years of operations, and 1 year of final data processing, data archive, and project shutdown.

SIM Lite uses only technology from the successful SIM technology development program completed in 2005. No technology funding is included in the cost estimates below.

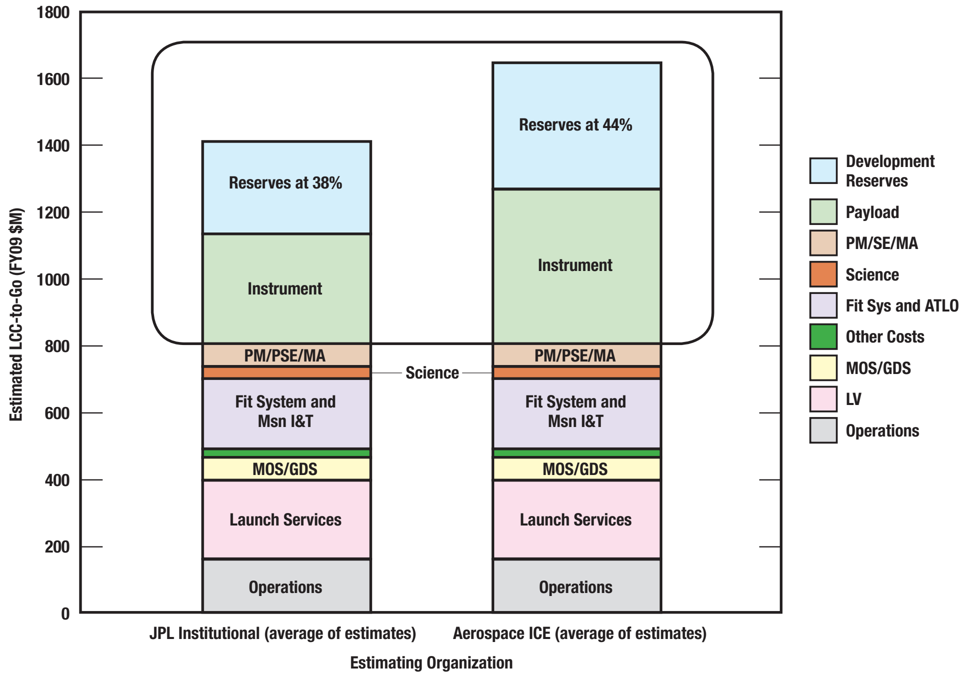
There are no current domestic or international collaborations for SIM Lite. The cost estimates quoted below are for a SIM Lite mission entirely funded by NASA.

SIM Lite Cost Estimate Preliminary Results

Phases BCD — Development cost-to-go: BCD cost-to-go results not including launch services include the JPL institutional estimate (average of the JPL estimates) of $1,110M FY09$ ($270M Phase B, $740M Phase CD), and the Aerospace ICE estimate of $1,260M FY09$ ($1,260M Phase BCD). Both estimates are at the 70% confidence level on the cost confidence curves generated by the respective organizations.

The differences between the JPL institutional and Aerospace ICE estimates are largely in the instrument and the budget reserves required to achieve 70% cost confidence (Fig. 6-1). The Aerospace instrument estimate is $460M FY09$, which is ~40% higher than the JPL instrument estimate of $330M FY09$. Similarly, the Aerospace budget reserves of $380M FY09$ are ~36% higher than the JPL budget reserves of $280M FY09$, part of which is reserve on the delta in instrument cost and part from the higher recommended reserve percentage of 44% (vs. JPL's 38%). This diversity is not surprising given the first-of-a-kind nature of the instrument.

FIGURE 6–1. *Comparison of SIM Lite and ICE estimated costs. The estimates differ in the projected costs of the instrument and the required reserves.*



The Aerospace project management, project system engineering, and mission assurance costs (PM/PSE/MA) of $88M FY09$, being a wrap on other costs, are also higher than the corresponding JPL estimate ($64M FY09$) by 38%. Other project element costs are roughly the same between the two estimates.

The higher Aerospace-recommended reserve percentage (44% vs. JPL 38%) derives from the slightly more conservative (than the JPL Engineering Cost Estimating Office) cost risk analysis assumptions used to generate the Aerospace cost risk analysis S-curve.

A cost for launch services was developed by NASA's Launch Services Program in March 2009. Based on SIM Lite's launch requirements, a launch services cost estimate range of $210M FY09$ to $270M FY09$ was submitted to NASA's Science Mission Directorate (SMD). The average value of $240M FY09$ was used above and in Table 6-1.

Phase EF — Operations and Closeout: The cost estimates for 5.3 years of operations and 1 year of post-operations data processing, data archive, and project closeout range from $150M (Aerospace ICE) to $160M (JPL Institutional), both in FY09$. See Fig. 6-2.

Science Community Funding: Based on the JPL institutional estimate, the science community would receive approximately 2/3 (~$20M FY09$) of the development science budget and 2/3 (~$100M FY09$) of the operations phase budget (Fig. 6-2), for a total of ~$120M FY09$.

Table 6-1 summarizes the Aerospace and JPL estimates.

TABLE 6–1. *SIM Lite Astrometeric Observatory cost, in constant year FY09$ at 70% confidence.*

Estimate Range	Phase B	Phases C/D	LSP	Phases EF	LCC-to-Go
JPL Institutional	*$270 M**	*$740 M**	*$240 M*	*$160 M****	*$1,410 M*
Aerospace ICE	*$1,260 M***		*$240 M*	*$150 M****	*$1,650 M*

Schedule durations: B-15 mo.; CD=43 mo.; EF=72 mo.
Phase definitions are at the end of this section.
* Includes 38% reserves.

**Includes 44% reserves. BCD cost breakout into Phase B and Phase CD was not provided.
***Includes 15% EF reserves.

SIM Lite Cost Estimate Validation

In addition to the model- and analogy-based independent cost estimate performed by the Aerospace Corporation, Aerospace also checked the validity using a tool called Complexity Based Risk Analysis (CoBRA) [2]. This tool uses up to 40 parameters to describe the mission and computes a complexity index relative to other missions in the Aerospace CoBRA database. The SIM Lite complexity index and cost is then plotted relative to ~110 other missions in the database (see Fig. 6-3).

The points in this plot are: Green-diamond = successful; Yellow-X = impaired; Red-X = failed; gray-diamond = yet to be determined.

The plot suggests that SIM Lite costs estimates by both JPL and Aerospace are consistent with successful missions of similar complexity.

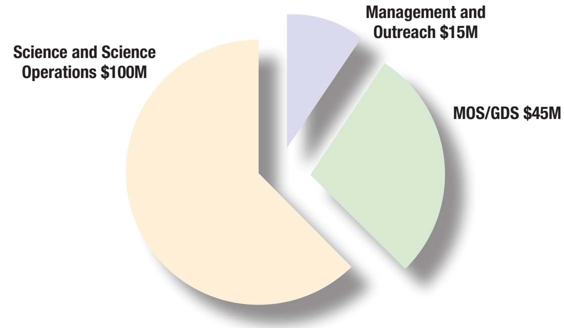
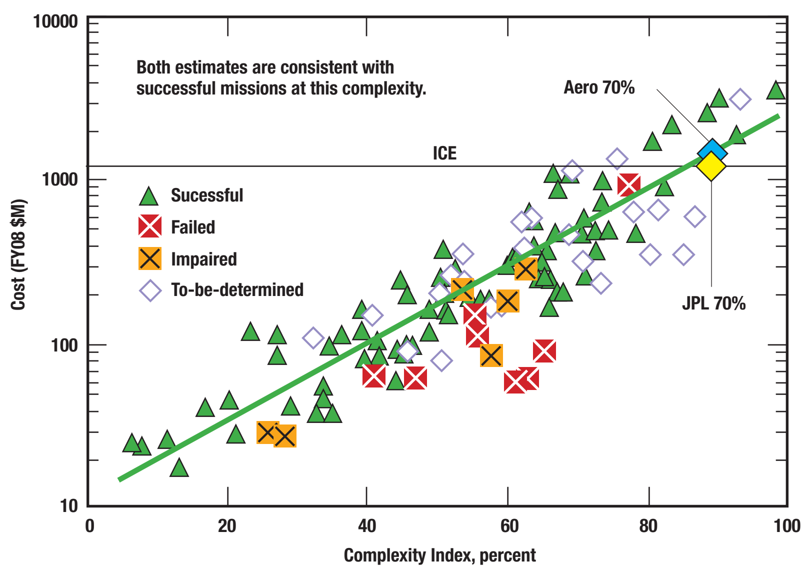


Figure 6–2. *SIM Lite estimated costs for operations and closeout. The JPL institutional estimates (shown) differ from the ICE estimates by about 7%.*

Figure 6–3. *SIM Lite cost estimate. This figure compares the SIM Lite estimated cost with those of other missions of varying complexity. This plot suggests that SIM Lite cost estimates by both JPL and Aerospace are consistent with those of successful missions of similar complexity.*



References

[1] The Aerospace Corporation, "SIM Lite Independent Cost, Schedule, and Technical Readiness Evaluation Assessment," NASA HQ Briefing, January 27, 2009.

[2] David A. Bearden, 2000, "A Complexity-Based Risk Assessment of Low-Cost Planetary Missions: When Is a Mission Too Fast and Too Cheap?," Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD.

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Phase F = Closeout

The work described in this report was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The cost estimates summarized in this document do not constitute an implementation-cost commitment on the part of JPL or Caltech.