National Aeronautics and Space Administration

SIM Lite

Astrometric Observatory

A Response to the
Request for Information
Part 2 from Astro2010,
the Astronomy and
Astrophysics Decadal
Survey Subcommittee
on Programs

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Jet Propulsion Laboratory
California Institute of Technology
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From Earth-Like Planets To Dark Matter

Response to the Request for Information Part 2 from Astro2010,
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)*

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Notes:

1. Tables associated with each section above are included immediately following each section.
2. References fro the Executive Summary and Sections 1 & 2 can be found on page 1-7.

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.

Executive Summary

This document is the SIM Lite Astrometric Observatory (hereafter, SIM Lite) response to Astro2010 RFI Part 2, dated 25 June 2009. Substantially more information is available than can be presented in this document. Between Oct 2008 and Jan 2009, the project worked closely with the Aerospace Corp (Bob Bitten, Robert Kellogg, Debra Emmons, and David Bearden) providing details for a Technical & Schedule Assessment and Independent Cost Estimate (ICE) as requested by NASA HQ. Aerospace Corp still has these far-more-detailed data in their records and has access to the originals in the SIM Lite project's electronic library.

The SIM Lite is a new implementation – more compact, reduced mass, more cost-effective – version of the astrometric mission called for in the 1990 (Bahcall) Decadal Survey Report [2], in which NASA has invested 15 years and $590M (RY$) to bring technology, mission design, and brassboard model hardware to a very mature state. SIM Lite 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. It will produce seminal results in four key science themes and provide for a General Observer program as described in Section 1. A brief history of events following the 2002 CAA review [20] is given in Section 2.

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 microarcsecond (μas) RMS 1-sigma in 1000 sec, with the ability to detect an exoplanet signature of 0.2 μas in a 5-year observational campaign. This will lead to the detection of extrasolar planets down to the mass of the Earth within the habitable zones of the nearest 60-100 stars. SIM Lite will achieve wide-angle astrometry at 4 μas RMS 1-sigma 5-year mission accuracy. The payload consists of a 6-m optical Michelson stellar interferometer (MSI) with 50-cm apertures, described in Section 3. The Mission Design and Spacecraft implementations are described in Sections 4 and 5, respectively.

No technology development remains. All technology was completed 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 Sections 3 & 6).

Mission operations and data reduction is described in Section 7.

SIM Lite is in NASA Phase B, prepared to complete its Preliminary Design Review and move into implementation in roughly a year, and could launch as early as 2015 (Section 8).

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 9, 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 was estimated to be $160M for 5.3 years of operations and one year of post-operations data archival. At the same time, an independent technical & schedule assessment and cost estimate was conducted by the Aerospace Corporation under contract to NASA HQ, producing a multiple model-based estimate of $1,260M plus launch services for development cost-to-go and $150M for operations, also in FY09$.

1 Science Overview

The science that can be accomplished by a space-based microarcsecond (μas) astrometric observatory, such as SIM Lite, has been extensively studied over the past three decades and briefly documented in three successive AASC Decadal Surveys [1-3]. Serious examination of the potential of such an observatory was undertaken by two working groups appointed by NASA: the Space Interferometer Science Working Group (SISWG) and later by the Space Interferometry Mission Science Working Group (SIMSWG) [4,5]. These two reports examined the broad array of science that could be accomplished by a pointed astrometric observatory with microarcsecond (μas) capability. They also examined the overlap/synergy between SIM and two astrometric survey missions: GAIA and FAME, with the SISWG concluding: "*Thus, the overlap between GAIA and SIM is much less than their complimentarity*." The SIMSWG reconfirmed the SISWG SIM/GAIA findings and examined the relationship between NASA's FAME mission (later canceled) and SIM. For a current assessment of the relationship between SIM and GAIA, refer to the SIM Lite book [6] (pages xviii, 13, 65, 84 and 128).

The first SIM Science Announcement of Opportunity (AO-1) was issued immediately following the SIMSWG Report, and SIM Science Teams were selected by NASA HQ in 2000 under a background assumption that both FAME and GAIA would fly. Ten Key Projects and five Mission Scientist teams were selected through this AO. Their proposals can be found on the SIM Lite website [7].

More recent assessments of SIM Lite science can be found in a major PASP paper by Unwin et al. [8]; the SIM Lite Book [6]; and the SIM Lite response to Astro2010 RFI Part-1 [9]. Additionally, eleven white papers were submitted to the Astro2010 Science Frontier Panels [10], several to each of the five panels. These papers describe how the science from a μas astrometric observatory, such as SIM Lite, fits into those five frontier themes. A good indication of the current relevance of SIM Lite can be found in the *SIM Science Studies*, a set of 19 contracts competitively selected in the fall of 2008, with the goal of exploring the science relevance of precision astrometry to modern astrophysics [11]. These teams are studying new ways of using SIM Lite's capabilities.

Astrometry's role in exoplanet discovery and exploration was formally reviewed in 2008 by the AAAC Exoplanet Task Force [12]. The Report's key finding relative to astrometry is significant:

"0.1.4 B. Recommendations for 6–10 Years…

Recommendation B. I. a. 1 – Launch and operate a space based astrometric mission capable of detecting planets down to the mass of the Earth around 60–100 nearby stars, with due consideration to minimizing the width of any blind spot associated with Earth's parallax motion. (This requires a mission precision, over many visits to a given star, as small as 0.2 microarcseconds.)."

The role of an astrometric mission in exoplanet finding and characterization was further examined at the 2008 Exoplanet Forum and reported in the Astrometry section of the Exoplanet Community Report [13]. The astrometry committee confirmed the findings of the Exoplanet Task Force and recommended: "*The committee's highest priority is to deploy a facility for micro-arcsecond astrometry of nearby stars during the 2010-2020 decade*."

The key role of exoplanet searches in SIM science was simulated in detail during 2008, using a 'double-blind' methodology (described in more detail below; Section 2.1.1). The goal was to find whether SIM Lite can detect and characterize the mass and orbit of terrestrial, habitable-zone planets in multiple-planet planetary systems. This study confirmed the ability of an astrometric mission of SIM Lite's capability to detect Earth-mass planets in the habitable zone of Sun-like stars. Sun Lite could do a complete search of the 60 best nearby candidate stars, regardless of planetary system configuration. A preliminary report has been published, and a detailed paper is in preparation [14,15].

Summary papers on several relevant issues to exoplanet finding can also be found on the SIM website [7]. These include papers on the effects of stellar noise on astrometry and radial velocity; astrometry's ability to find exo-Earths in the presence of star spots; and the synergy of astrometry and direct-detection in measuring the orbits of exo-Earths in multi-planet systems [16-18].

Rather than restate the detailed science case, which has been laid out in the SIM Book [6], the PASP paper [8], and the Astro2010 White Papers [10], we concentrate below on answering the specific science questions posed by the Panel. As SIM Lite is a general-purpose observatory, with a wide range of science objectives, we focus more on the measurement capabilities that enable the science. SIM Lite is more capable than the version of SIM that was recommended in the 1990 (Bahcall [2]) and 2000 (McKee Taylor [3]) Surveys. In the intervening 9 years, almost none of the original science has been accomplished by other means, or the scientific questions superseded.

However, for one of the most important science themes, the astrometric search for Earth-like planets, we provide a more quantitative analysis of the capability under different assumptions of performance (Section 1.6). We show that the science recommended by the AAAC Exoplanet Task Force [12] can be accomplished by SIM Lite. Just as significant, as a flexibly-scheduled observatory, the actual program of planet searching and characterization will of course take full advantage of the state of knowledge in the field at the time of SIM Lite launch.

Astro2010 RFI Part 2 requested answers to the following science questions:

1.1 Describe the measurements required to fulfill the scientific objectives expected to be achieved by your activity.

The SIM Lite Astrometric Observatory is designed to perform just one kind of measurement – precision astrometry – that enables its entire science program. Each science objective is achieved by measuring the astrometric signature of the object under study. In almost every case, the astrometric signal is a function of time, arising from dynamical processes, which have a simple, well-defined functional form, and consists of repeated measurements (made over days to years) to extract the signal.

SIM Lite measures many kinds of astrometric signatures, the most important being:

a. Parallax (10 μas in a single measurement; 4 μas mission accuracy using multiple measurements; all in an absolute reference frame)
b. Proper motion (2.5 μas/yr mission accuracy)
c. Orbital motion (< 0.2 μas minimum detectable astrometric signature in a narrow-angle reference frame after 200 measurements over 5 years; used for terrestrial, habitable-zone planet detection)
d. Center of light motion (e.g. in blazars; narrow-angle frame; and color-dependent relative astrometry)
e. Accelerations (e.g., long-period planets; Galactic rotation)

1.2 Describe the technical implementation you have selected, and how it performs the required measurements.

SIM Lite is a Michelson stellar interferometer (MSI), operating in the optical waveband. Because most of the targets are stars that are unresolved by the instrument, the most accurate way of measuring positions is with the highest angular resolution. A filled aperture is not necessary, and at the microarcsecond level, dealing with systematics and time dependences of centroiding a point-spread function to extreme precision are very challenging. In contrast, a dilute aperture interferometer delivers a signal that is a pure sine wave. Not only is the measurement process vastly simplified, systematic errors are much easier to control. Errors can enter only through the length and orientation of the interferometer baseline, and in SIM Lite, these are monitored to the required precision.

Most challenging for SIM Lite is the narrow angle astrometric measurement of a bright star relative to ~4 nearby dimmer reference stars. One can compare the photon-limited precision of an interferometer with a filled aperture telescope using the following simplified example (taken from the SIM Lite book [6], Section 16.1). The width of a diffraction-limited image for a telescope is 2.44 λ/D, and $\lambda/(B)$ for an interferometer. The number of photons collected by an interferometer is $2d^2$, versus D^2 for a telescope. Here D is the diameter of the large telescope, d the diameter of the small telescopes in the interferometer and B the baseline. Photon limited performance is the same for a telescope and interferometer when $D^2/1.22 = 2*B*(\sqrt{2}*d)$. From this equation, SIM Lite is equal to a 3.2 m filled-aperture telescope. But for narrow angle astrometry, photon noise from the reference (~9 mag) stars by far dominates the photon noise from the bright target star (~7 mag). In general, photon-limited accuracy is approximately proportional to the diameter of the field being observed. SIM Lite with a 2 degree field of regard for 1μas astrometry would be able, on average, to find reference stars that are >100 times brighter than a telescope with a 12 arcmin field. Photon limited performance of the target-to-reference star position for SIM Lite is therefore equivalent to a filled aperture telescope of 32 m diameter and a 12 arcmin field focal plane with 4x10^11 pixels.

Detailed information about how SIM Lite measurements are made can be found in the SIM Lite Book [6]. In brief, the SIM Lite science interferometer observes targets sequentially within its 15-deg field of regard for a single spacecraft pointing (referred to as a "tile"). The entire 4pi sr sky is covered sequentially during a one-year period by 1302 overlapping "tiles" such that a global solution tying all observations together can be achieved during ground processing. To stabilize the baseline orientation during and between targets, SIM Lite continuously observes two guide stars, one using a Guide-1 MSI co-bore-sighted with the center of the science MSI 15-degree field of regard, and the second with a 30 cm telescope oriented orthogonal to the plane defined by the science/first-guide MSI baseline and their look direction. To monitor changes in the baseline length and the alignment of the science interferometer, a laser metrology 'truss' measures changes in the lengths of critical dimensions in the instrument.

1.3 Of the required measurements, which are the most demanding? Why?

Narrow-angle astrometric measurements in support of SIM Lite's planet-finding science are the most demanding because they require the most accurate astrometry of all of the science objectives. Narrow-angle measurements are made between a bright (6-7 mag) target star and multiple (~4) nearby (≤ 1° from the target star) ~1 kpc K-giant reference stars (~9 mag) by sequentially chopping between the target and reference stars.

There are two narrow angle requirements. One is the control of random instrumental errors so that photon noise from the reference stars is the dominant error term in achieving 1 μas accuracy in a 1000 sec observation. The second, more challenging requirement, is the control of systematic errors so that many 1 μas measurements can be averaged over the 5 year mission to detect a 0.2 μas periodic signal with a SNR ~ 6; a mission level precision of 0.035 μas. This last requirement has been a major topic of the last several years of project activity. The most recent lab results show that instrumental random noise is below 0.2 μas in a 1000 sec chopped measurement, well below the photon noise from reference stars. Also recently demonstrated in the lab were: (1) control of systematic errors for long integrations down to ~0.04 μas for day-long integrations, and (2) methodology for calibrating the fringe position shift due to star color change as the instrument chops between target and reference stars [19].

1.4 Present the performance requirements (e.g. spatial and spectral resolution, sensitivity, timing accuracy) and their relation to the science measurements.

For parallax measurements, SIM Lite's accuracy is limited to that of the global reference frame defined by 1302 references stars (K Giants at ~1 kpc) with RMS accuracy 4 μas. At this accuracy, a star at 2.5 kpc has an absolute distance known to 1%. At 25 kpc, the distance is accurate to 10%. The ~10 (minimum) parallax measurements must be spread over 1.5-2 years, to allow a separation between parallax and proper motion (which must always be solved for as well).

For planet finding (or orbit determination of binaries etc.) the equivalent end-of-mission positional accuracy in a narrow-angle frame is better than 0.035 μas, providing a minimum detectable astrometric signature below 0.2 μas after 200 measurements spread out over the mission duration. This is better than the accuracy required for the detection of a planet with a signature of 0.3 μas at an SNR≥5.8 – the signal of a 1-Earth mass planet in a 1-AU orbit around a Sun-like star, observed from a distance of 10 pc. A typical observing cadence would visit the target star every 1 to 2 weeks for the duration of the mission.

Planetary mass determination also requires the distance to the star; for nearby stars, distances are already known well, but extremely accurate distances come for free with SIM Lite. These stars are all too bright for Gaia, which in any case has single-visit accuracy about a factor of 70 worse than SIM Lite's.

The instrument efficiency is determined by how rapidly it achieves its measurement precision on-target and how quickly it can move to and acquire the next target. In addition to the already selected (via AO-1 in 2000) science and a small astrophysics GO program, SIM Lite can support a planet-search program that observes 60 of the nearest FGK stars for 1-Earth-mass planets orbiting in the center of the 'habitable zone'.

Details of the SIM Lite Astrometric Error Budget (AEB), that relates lower level performance requirements to top level astrometric performance, are beyond what can be supplied within the page limitations of this RFI response. These details are, however, available in Chapter 18 of the SIM Lite Astrometric Observatory book [6].

1.5 Present a brief flow down of science goals/requirements and explain why each payload instrument and the associated instrument performance are required.

SIM Lite has a single science instrument – a Michelson stellar interferometer whose sole task is to perform ultra-precision astrometry. It is an *observatory class mission*, whose science objectives were specified to meet broadly articulated science goals. Its capabilities have their source in the 1991 Bahcall Report [2], which defined a mission capable of a range of science at 30 μas, with 3 μas as a 'stretch goal'. SIM Lite specific requirements trace most directly to the SIMSWG, a NASA-selected working group. Their Report [5] informed the mission capabilities described in the science AO-1 (2000) that selected the SIM Key Projects. Subsequently, the science program was endorsed by the 2000 McKee-Taylor Report [3] and by the 2002 NRC/CAA review [20] both of which recommended a more-challenging wide-angle goal of 10 μas. Finally, the AAAC Exoplanet Task Force [12] made a specific recommendation that an astrometry mission should search a minimum of 60 nearby stars for Earth-mass planets in habitable zone.

The broad science goals define a performance 'envelope' that can be summarized as follows:

a. Wide-angle *mission* accuracy: 4 μas (RMS, defined by a grid of reference stars)
b. Narrow-angle *single measurement* accuracy: 1 μas
c. Limiting magnitude: V=20 (ability to retain full accuracy at this magnitude)
d. Bright star limit: V=-1.4 (Sirius)
e. Narrow-angle systematic noise floor: 0.035 μas (bright target)

The following key parameters derive from the science requirements of precision astrometry:

f. Long baseline (SIM Lite is 6-m; longer baselines produce better accuracies but requires a larger, more massive structure to withstand launch)
g. Optical wavelength (CCD efficiency is high; short wavelength allows better fringe measurement)
h. Primary optics are 50-cm diameter (needed for astrometry of faint targets; larger optics provide better sensitivity to dim targets but are heavy and have more stringent requirements on surface figure and stability).

1.6 For each performance requirement, present as quantitatively as possible the sensitivity of your science goals to achieving the requirement. For example, if you fail to meet a key requirement, what will the impact be on achievement of your science objectives?

The objective of the narrow angle exoplanet deep search program is to find terrestrial planets (0.3 to 10 Earth masses) in the habitable zone (HZ) (0.75 to 1.8 AU, scaled for stellar luminosity) of 60 to 100 *nearby* stars that are suitable for spectroscopic characterization by a direct detection mission, and to determine the mass and orbital parameters of any planets found.

Astrometric planet finding capability is a function of narrow-angle single-measurement accuracy (SMA) and the planet mass search depth attempted for each star. SIM Lite's search 'depth' is one Earth mass planet at "mid"-HZ (1 AU equivalent) for all stars searched. This would include, for instance, 0.6 Earth mass planets at the outer edge of the HZ. The amount of observation time required goes as the inverse of the planet mass squared, so deeper searches (smaller planets) require more observing time.

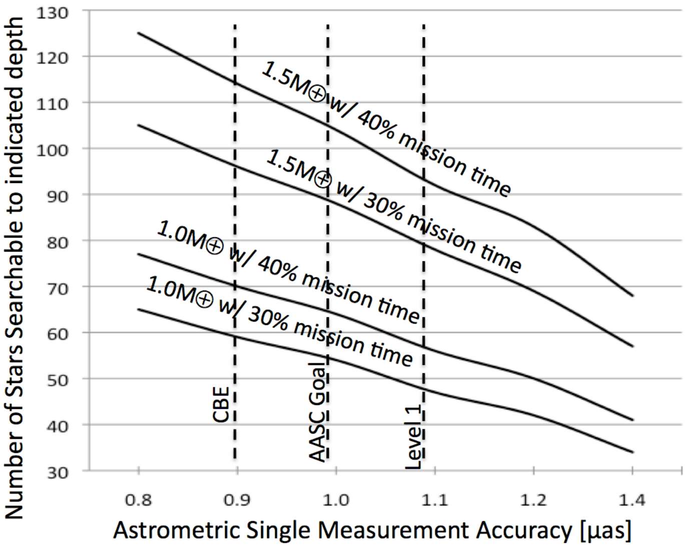

Figure 1.6-1: SIM Lite planet search capability, showing the number of stars searched to a given mass sensitivity, as a function of instrument performance. Current best estimate (CBE) is 0.9 µas in 1200s of observing time. Curves are shown for 1.0 and 1.5 Earth-mass planets at "mid" HZ (1 AU scaled for stellar luminosity), for either 30% or 40% of the mission devoted to this project. Note that even at 1.0 µas, SIM Lite meets the Exoplanet Task Force recommendation.

Figure 1-6-1 shows the number of stars searchable to 1.0 and 1.5 Earth masses using either 30% or 40% of SIM Lite's science observing time. The current best estimate (CBE) of SIM Lite's SMA is 0.9 µas, which would allow 70 of the astrometrically best nearest stars being searched to one Earth mass depth at the mid HZ using 40% of SIM Lite's mission time. The curves show that the exoplanet science is very robust to changes in astrometric performance.

The actual planet search strategy (number of stars, search depth, etc.) will of course be based upon prior knowledge, primarily from Kepler results. If Kepler finds that terrestrial, habitable zone (T/HZ) planets are common, then a deeper search (for smaller planets) of fewer stars is likely. If, on the other hand, Kepler finds that such planets are rare, then a shallower search (larger planets) of more stars would provide a higher probability of finding planets for imaging mission follow-up.

From a basic physics or technology point of view, the project is confident that the requirements can be met. However when building flight hardware, on a not very flexible schedule and even less flexible budget, some contingency is needed. Based upon the recent experience of building and testing flight-like hardware for all major instrument assemblies, the project is confident that, if the requirements aren't met, they will be missed by 10's of percent, not factors of two.

For high precision wide-angle astrometry/parallaxes, the story is similar. Narrow angle precision is the driving requirement for control of systematic errors for SIM Lite. Factors of several degradation in narrow-angle performance would have virtually no impact on wide-angle performance or wide-angle science. Wide-angle science with SIM Lite is concentrated on stars fainter than 15 mag, where Gaia's accuracy rapidly degrades, so reduced optical throughput or lower performance CCDs are factors which would most impact wide-angle science but that are not likely to be an issue for SIM Lite. Overall, the impact of not meeting microarcsec requirements on SIM Lite will have an almost negligible impact on wide-angle science.

1.7 References in Executive Summary, Science Overview, and Programmatic, History

Most of the (non-journal) documents can be downloaded from the SIM Lite website, at http://sim.jpl.nasa.gov.

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2 Programmatic, Cost & Science History

2.1 Activities ranked in either the 2000 "Astronomy and Astrophysics in the New Millennium" survey or in the "Beyond Einstein Program Assessment Committee" should provide up to four (4) additional pages describing the changes in the activity science goals, technical implementation, and/or estimated cost since AANM and the most recent previous NRC report. We need to understand your explanation of changes that significantly affect the scientific return, the activity risk, and/or estimated cost of the activity, and the reasons for them.

2.1.1 Programmatic history since the May 2002 CAA SIM assessment [20]:

The SIM Project's May 2002 CAA briefing described the SIM 2001 redesign, science capability and state of technology development at that time. This design was STS (Shuttle) launched with two 10-m science Michelson stellar interferometers and two guide interferometers, tied together with an external metrology truss.

In April 2003, the project held a Preliminary Mission and System Review (PMSR) and Initial Confirmation Review (ICR) with NASA HQ. Following completion of a few actions from these reviews, NASA HQ directed the project to enter Phase B on August 1, 2003. A successful Mission-level System Requirements Review (SRR) was held in November 2003.

Meanwhile, back on February 1, 2003, less than a year after the CAA briefing, the shuttle Columbia, SIM's ride to orbit, was lost, prompting a July 22, 2003 letter from NASA HQ directing the project to redesign the project to launch on an Evolved Expendable Launch Vehicle (EELV). This redesign, completed in December 2004, resulted in shortening the science baseline from 10 m to 9 m to fit within EELV launch faring constraints. Because of the continued success of the SIM technology program, this shortening of the baseline did not result in reduction in science capability.

While the science performance of the EELV redesign was unchanged, the cost wasn't, prompting a January 21, 2005 NASA HQ direction memo to redesign SIM to fit a $1.2B FY05$ Phase C/D cost cap. This redesign was completed July 27, 2005, meeting all of the constraints imposed by the HQ direction letter. Meeting these objectives required removing of one of the two science interferometers, mitigated by adding redundancy in the remaining interferometer.

The SIM technology program is complete. Its last major milestone was met in July 2005. Formal technology program closeout reviews and official signoffs were completed in March 2006. The resulting predicted SIM performance gave 40% margin on the NRC recommended 'goal-level' performance for both Wide and Narrow angle astrometry for the then 9m version of SIM, far better than anyone expected when the technology program began. It was this large performance margin that enabled the SIM Lite design.

As the project ramped up towards holding PDR by the end of 2006, large cost growth in the JWST project made it clear to NASA that it could not afford to proceed with SIM until JWST was completed, well into the next decade. This prompted NASA to severely reduce SIM funding, defer the launch date indefinitely, and direct the project to enter an "engineering risk reduction" period where limited funds would be used to retire as much instrument development risk as possible. These activities include building brassboards (form, fit and function to flight) of key instrument assemblies and subjecting these to full flight qualification-level environments and rigorous pre/post environmental performance testing. This would allow proceeding directly to protoflight units (bypassing engineering models) when development continues. These engineering risk reduction activities will continue through the end of FY2010, when all major instrument assemblies will have been brassboarded and tested.

In 2007, the project undertook, on its own initiative, to explore the lowest cost alternative designs that could be accomplished with the completed SIM technology. This led to the concept that we now call the *SIM Lite Astronomical Observatory*, to distinguish it from the earlier designs. The key fact here is that the already-complete technology program allows SIM Lite to fully meet the 'goal level' performance specified in the 2000 Survey [3]; and also of fully meeting the Exoplanet Task Force objectives [12]. SIM Lite took advantage of the excess performance margin of SIM over the 2000 Survey goals, allowing simplifications that reduced performance to that level (4 μas wide-angle, 1 μas narrow-angle). Major changes in SIM Lite include reducing baseline from 9 m to 6 m, replacing the Guide-2 interferometer with a 30 cm Guide-2 telescope. One major change represented an increase in capability: science siderostat diameter went from 30 cm to 50 cm, retaining the dim star performance for astrophysics.

In January 2008, NASA HQ asked the Exoplanet Exploration Program (ExEP, then Navigator) and the Project to study whether SIM Lite would be capable of detecting Earth mass planets in the habitable zone around nearby stars out to 10 pc in complex planetary systems like the Solar system. The importance of this study was underlined by the NASA's Astronomy and Physics Director, Jon Morse, who defined the goals and approach. This 'double blind' study was undertaken in two parts (a) with 40 stars (for simplicity all taken as the Sun and at 10 pc) but with varying planetary system architectures, and (b) with 60 actual SIM target stars also with varying planetary system architectures. The results convincingly showed that SIM Lite can perform these searches as claimed, and that confusion from other planets is not an issue. Only in a few pathological cases did it have difficulty with the simulated data.

This 'double blind' study should serve as a model for other missions seeking to demonstrate their capability in realistic observing situations. Simulation allows a variety of realistic issues to be included, and is preferable to analytical methods, which may be too idealized. Another benefit of the double-blind approach is that it engages a community that might otherwise be skeptical of the results. In the SIM Lite study, simulated data were generated from systems created by several groups, and the data distributed to a set of 5 analysis teams, four of which were competitively selected. The analysis teams worked independently until the results were all assembled; the teams had information on the format, but not the content, of the data. The results from the five analysis teams were combined by a team led by the ExoPlanet Exploration Program (ExEP) Chief Scientist, and the entire process was overseen by the NASA-appointed ExEP External Independent Readiness Board (EIRB).

An important result was that planets were recovered from the data at levels that verified the analytical predicted performance. And that the best of the teams were both efficient (i.e. recovering planets should have detected), and reliable (not claiming detections which were in fact noise). This built confidence that this problem is now well-understood. A preliminary report has been published, and a major journal paper is in preparation [14,15].

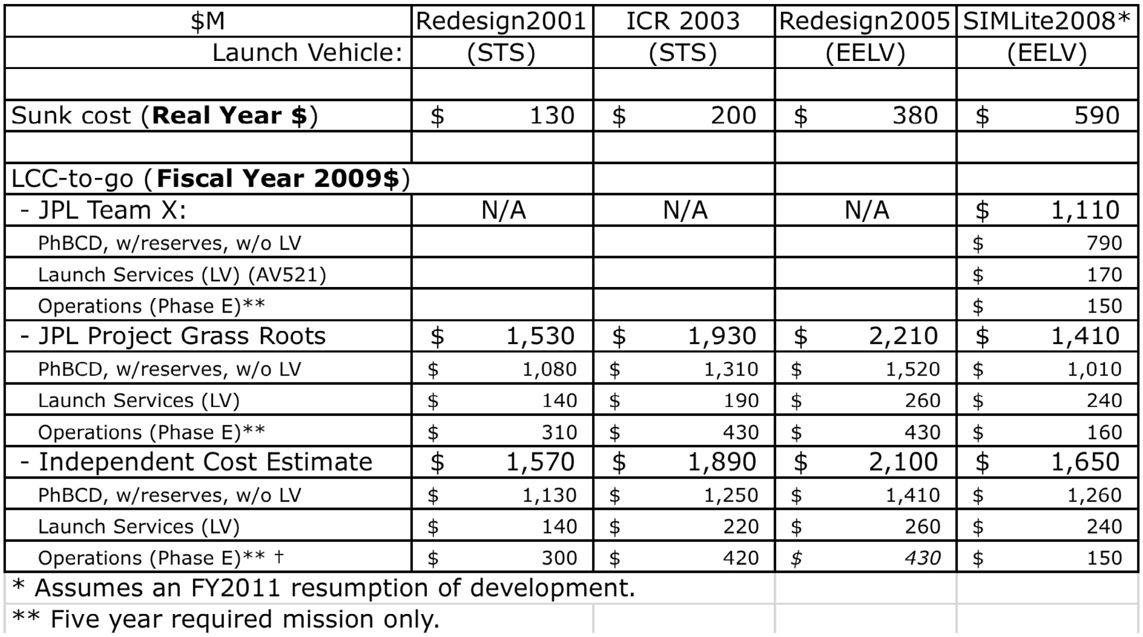
A similar study is currently being formulated by the ExEP office for evaluating the claimed capabilities of direct-detection exoplanet missions. Detailed simulations, and significant community participation, are major ingredients in reaching a consensus among the various claims currently being made. This study should start in the Fall of 2009.

2.1.2 Cost History since 2002:

Table-2.1.2-1 provides a cost history since the 2002 CAA review. This table shows the sunk cost to date in Real Year dollars at the top and the Life Cycle Cost To Go (LCC-to-go) in constant Fiscal Year 2009 dollars. Sunk costs are useful only in evaluating how much confidence there should be in the future cost estimates (i.e., has enough effort been expended to ensure that the design is well enough understood so that future cost estimates can be expected to be reasonably stable?). Future costs are presented in FY09$ since the only reasonable way to compare alternative mission concepts with different cost profiles and different science returns is to compare the present value of future cash flows against the present value of the potential science return.

The table presents three different cost estimates (Team X, JPL Project, and Independent Cost Estimate) for four cost estimation events (2001 Redesign – prior to the CAA review, 2003 Initial Confirmation Review, 2005 Redesign, and 2008 SIM Lite). Note that Team X has estimated only the most recent (i.e. SIM Lite) design, which is provided here for comparison with the Team X (or IDC) estimates of the recent Astrophysics Strategic Mission Concept Studies (ASMCS).

Table 2.1.2-1: Cost estimate history since the SIM 2002 CAA review, $M



$M	Redesign2001	ICR 2003	Redesign2005	SIMLite2008*
Launch Vehicle:	(STS)	(STS)	(EELV)	(EELV)
Sunk cost (**Real Year $**)	$ 130	$ 200	$ 380	$ 590
LCC-to-go (**Fiscal Year 2009$**)				
- JPL Team X:	N/A	N/A	N/A	$ 1,110
PhBCD, w/reserves, w/o LV				$ 790
Launch Services (LV) (AV521)				$ 170
Operations (Phase E)**				$ 150
- JPL Project Grass Roots	$ 1,530	$ 1,930	$ 2,210	$ 1,410
PhBCD, w/reserves, w/o LV	$ 1,080	$ 1,310	$ 1,520	$ 1,010
Launch Services (LV)	$ 140	$ 190	$ 260	$ 240
Operations (Phase E)**	$ 310	$ 430	$ 430	$ 160
- Independent Cost Estimate	$ 1,570	$ 1,890	$ 2,100	$ 1,650
PhBCD, w/reserves, w/o LV	$ 1,130	$ 1,250	$ 1,410	$ 1,260
Launch Services (LV)	$ 140	$ 220	$ 260	$ 240
Operations (Phase E)** †	$ 300	$ 420	*$ 430*	$ 150

* Assumes an FY2011 resumption of development.

** Five year required mission only.

2.1.3 Science Performance History since 2002:

The CAA's 2002 letter to NASA described the changes in the SIM science capabilities between the 1990 decadal report and of FY2002. The performance table from the CAA 2002 report is reproduced in Table 2.1.3-1, augmented with changes since that time.

As of 2002 SIM technology testbeds had demonstrated 3.2 µas wide-angle astrometry, better than the 4 µas goal of the 2002 plan. In narrow angle astrometry had only achieved 1.7 µas demonstrated laboratory performance versus a goal of 1.0 µas; by 2005 this goal was reached.

Since the 2002 report, the SIM mission has undergone several design revisions, as described above. The baseline length was decreased from 10m first to 9m to allow an EELV launch, then to 6 m in the current lower-cost SIM Lite design. The science telescopes were increased from 30 cm to 50 cm to preserve the dim star astrophysics program. From a photon limited perspective, the astrometric precision for a 1000 sec observation is proportional to ~ 1/(diameter*baseline), so the increase in aperture almost exactly balances the decrease in the baseline.

The wide-angle (astrophysics) science case is essentially unchanged since the CAA 2002 report. The CAA report recommended that a 30 µas wide-angle accuracy (as recommended by Bahcall) would adversely impact the astrophysics science and a 10 µas accuracy was more in line with the 2001 UVOIR panel report. Since the current SIM Lite design will achieve better than 4 µas for wide-angle astrometry, the science potential of SIM Lite is essentially unchanged since the 2001 UVOIR report.

Exoplanets are an exciting and fast-moving field, and the SIM Lite exoplanet program has evolved to take account. Over 350 exoplanets have now been found outside our solar system. A large number of Jovian and Neptune mass planets have been found, and the Kepler mission is expected to find perhaps 1000 more Jovian and Neptune sized planets, plus terrestrial, habitable-zone planets, transiting their parent stars. All of these will be a distances of roughly 1 kpc, too far for direct detection mission follow-up.

The next major frontier for a next generation space exoplanet mission, e.g., SIM Lite, is the discovery of Earth-mass planets in the habitable zone around *nearby* stars – those that can subsequently be observed with a direct-detection mission to measure their spectra. This was recognized by the AAAC

Table 2.1.3-1: Performance history of SIM. The Current Best Estimate (CBE) values are validated through the (completed) technology testbed program and integrated modeling at the system and subsystem level.

Mission name (review/date)	Wide-Angle Astrometry (mission)		Narrow-Angle Astrometry (single measurement)				
	Requirement (µas)	Goal (µas)	Requirement (µas)	Goal (µas)	Magnitude Limit (V)	Nulling?	Synthesis Imaging?
SOI (AASC/1982)	"Space Optical Interferometer (SOI) with resolutions of 1 to 10 µas by early part of next century."						
AIM (AASC/1991)	30	3	-	-	20	No	No
SIM (AASC/2000)	10	4	3	1	20	Yes	Full UV plane from 1 to 10-m
SIM (CAA/2002)	10	4	3	1	20	No	10-m baseline (plus rotation)
SIM (CAA/2002) CBE performance	3.2 µas		1.7 µas		20	No	9-m baseline (plus rotation)
SIM PlanetQuest (CBE performance 2005)	2.4 µas		0.7 µas		20	No	9-m baseline (plus rotation)
SIM Lite (CBE performance 2009)	4 µas		1 µas		20	No	6-m baseline (plus rotation)

Exoplanet Task Force [12] in their recommendation that an astrometric mission precede a direct detection mission. The Task Force recognized (1) the huge significance of a definitive catalog of Earth-mass planets around nearby stars (with accurate masses and orbits); and (2) the importance of such data in making the most effective use of a direct-detection mission's observing time.

Direct-detection missions (especially external occulters) are inefficient at discovery, and their scientific payoff is obviously in delivering optical and/or IR spectra. *Discovery* of an Earth-mass planet in the habitable zone requires two key measurements: one, a measurement of the mass of the planet, which is only possible with astrometry, and, two, the measurement of its orbit. Without a measurement of both the mass and orbit, a single coronagraphic image of a planet can only suggest the presence of a terrestrial, habitable zone planet. While SIM Lite can only deliver accurate *at-epoch* positions on the sky in the most favorable cases, in all cases it provides mass, orbit semi-major axis and orbital inclination, all required to confirm the discovery of a terrestrial, habitable zone planet. This is the existence proof – that a star *has* an Earthlike (terrestrial, habitable-zone) planet (or that it does not), critical information for a follow-on mission whose main goal is spectroscopy, not discovery.

Finally, we note that only about half of the SIM science observing time has been allocated to the first SIM Science Team, leaving about half for a General Observer (GO) program. This program will be a major opportunity for the science community and will consist of both astrophysics and exoplanet science. It will support both large programs (perhaps including topics not selected via AO-1) and small (e.g. precision parallaxes or binary orbits for a handful of carefully selected targets). But we expect that a large fraction will go to the exploration of exoplanets – the architectures and dynamics of systems containing multiple planets being just one example. The exact selection would be made, as it should, through independent peer-review.

3 Technical Implementation - Payload Instrumentation

3.1 Describe the proposed science instrumentation, and briefly state the rationale for its selection. Discuss the specifics of each instrument (Inst #1, Inst #2 etc) and how the instruments are used together.

The SIM Lite payload consists of a single large optical instrument that makes sequential astrometric measurements of the positions of stars projected along the interferometer baseline. As described in Section 1, the primary instrument sensor, a Michelson Stellar Interferometer (MSI), was selected due to the simple interference waveform from an optical MSI that allows precision angle measurements on the sky, i.e., precision astrometry.

The SIM Lite single optical instrument consists of four fundamental “optical sensors”: (1) the Science MSI, (2) the Guide-1 MSI, (3) the Guide-2 high-accuracy star-tracking telescope and (4) the external metrology, all mounted on a Precision Support Structure (PSS), a graphite reinforced polymer tubular structure with titanium joint fittings, which functions as a highly stable optical bench.

Each of these “optical sensors” is constructed from similar “subsystems” as follows: (1) the Science and Guide-1 MSI “sensors” each consist of two Collector Subsystems, one Astrometric Beam Combiner subsystem, and contain components of the External Metrology subsystem; (2) the guide-2 telescope “sensor” consists of components from the Collector Subsystem and the Astrometric Beam Combiner subsystem; (3) the External Metrology subsystem “sensor” is a distributed system with its components installed within the Collector and Guide-2 telescope subsystems. Each of these “sensor” subsystems are mounted to the Precision Structure Subsystem and all are supported by the Metrology Source and Control Electronics Equipment.

It is convenient to think of the “optical sensors” rather than the specific subsystems or assemblies because during instrument integration and test, individual “optical sensors” are tested as a unit.

It is also convenient to think of the guides together as a µas three-axis star tracker to stabilize the orientation of the science interferometer, especially during long dim-star integrations where there are insufficient photons to close the pointing loop on the science target itself.

3.2 Indicate the technical maturity level of the major elements and the specific instrument TRL of the proposed instrumentation (for each specific Inst #1, Inst#2 etc), along with the rationale for the assessment (i.e. examples of flight heritage, existence of breadboards, prototypes, mass and power comparisons to existing units, etc). For any instrument rated at a Technology Readiness Level (TRL) of 5 or less, please describe the rationale for the TRL rating, including the description of analysis or hardware development activities to date, and its associated technology maturation plan.

Table 3.2-1, SIM Lite Instrument MEL Part-1 with Technology Readiness Level and Basis, provides the list of subsystems and assemblies from which the SIM-Lite instrument “optical sensors” are constructed. For each assembly, the TRL and rationale for the assessment, such as performance testing on breadboard (bb) models or performance and environmental testing on Brassboard (BB) models, is provided. The table also provides technology readiness at the sub-system or instrument system level and the rationale for the assessment, based on performance testing on sub-system or instrument system demonstrations using a combination of breadboard and Brassboard components.

The Instrument System and Sub-systems are rated at TRL6. The technology required to perform the science has been demonstrated in the relevant vacuum environment, with thermal and mechanical stability conditions worse than those expected on orbit, using a suite of hardware and software testbed demonstrations.

A few assemblies (Siderostat mechanism, Long Stroke Optical Delay Line mechanism, Triple Corner-Cube optic, Metrology Source Optical Bench, Acousto-Opto-Modulators, Laser Pump Diodes, Metrology control and read electronics and Strain Gauge read electronics) are rated TRL5. Breadboards of those assemblies have met the required performance, but Brassboard or Engineering Models still need to be built to demonstrate TRL6. The steps required to achieve TRL6 are described in Section 6.

3.3 In the area of instrumentation, what are the three primary technical issues or risks?

3.3.1 Full Instrument Verification cannot be done during System I&T. Building a pseudostar to simulate three stars in the correct positions for the science and two guides is impractical. Instead, Instrument Verification will be done as a suite of "optical sensor" verifications, tied together by system modeling. Although various studies, including technology gate number eight, which was heavily reviewed and approved by NASA, have shown that this approach is appropriate for system verification, there is still a residual risk that some errors or subsystem interactions might have been missed in the analysis, leading to increased cost/schedule during instrument integration and test or reduced on-orbit performance.

3.3.2 The Instrument is not fully redundant. A Selected Redundancy Approach consistent with other large observatories has been used on SIM Lite. There is a risk that, at some future time, additional redundancy could be directed as a result of future external review, which might lead to increase mass, cost and complexity of the Instrument to meet the more conservative redundancy posture.

3.3.3 On-orbit Instrumental Error Calibration may require more calibration time than allocated in the current Design Reference Mission, which would affect mission throughput.

3.4 Fill in entries in the Instrument Table. Provide a separate table for each Instrument (Inst #1, Inst #2 etc). As an example, a telescope could have four instruments that comprise a payload: a telescope assembly, a NIR instrument, a spectrometer and a visible instrument each having their own focal plane arrays.

See attached Table 3.4-1.

3.5 If you have allocated contingency please include as indicated along with the rationale for the number chosen. If contingency is unknown, use 30% contingency.

Mass contingency is allocated at the component level depending on the design maturity, varying from 50% for conceptual design to 10% for previously built components. The roll-up mass contingency is 31%, consistent with the overall design maturity. Power contingency is set at 30%, consistent with the overall design maturity. Science data contingency is set at 43%, to allow for growth.

3.6 Fill in the Payload table. All of the detailed instrument mass and power entries should be summarized and indicated as Total Payload Mass and Power as shown in the table.

See attached Table 3.6-1.

3.7 Provide for each instrument what organization is responsible for the instrument and details of their past experience with similar instruments.

The SIM instrument will be fully developed by the Jet Propulsion Laboratory. JPL has extensive previous experience building ground based interferometers, including the Mark III interferometer on Mount Wilson, CA, the Palomar Test Interferometer on Palomar Mountain, and the Keck Interferometer in Hawaii. While a long baseline MSI has never been flown in space, JPL has been developing the technology for space interferometry since the early 1990's and has been leading the SIM instrument development since the beginning of phase A, in 1997. Total SIM instrument technology development and instrument design expenditures to date, nearly all fully relevant to SIM Lite, are about $400M real-year dollars (~2/3 of the $590M sunk cost to date) over the past thirteen years.

3.8 For the science instrumentation, describe any concept, feasibility, or definition studies already performed (to respond you may provide copies of concept study reports, technology implementation plans, etc).

SIM Lite has demonstrated all of the technology and engineering needed for the flight instrument by constraining the design to use only demonstrated SIM technology (components, subsystems & systems). 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. More information about the SIM Instrument technology development program can be found in the following documents:

- "Section 3, Technology Drivers," section of the SIM Lite Asro2010 RFI Part-1,
- Marr, J.C, *SIM Technology White paper for the Exoplanets Task Force*, Jet Propulsion Laboratory, California Institute of Technology on the SIM Lite public web site at URL: http://planetquest.jpl.nasa.gov/documents/TechExoPTF_Final.pdf
- Laskin, R.A., *Successful Completion of SIM-PlanetQuest Technology*, SPIE conference on Astronomical Telescopes 2006, also on the SIM Lite public web site at URL: http://planetquest.jpl.nasa.gov/documents/SPIE_06-rev6_small.pdf

3.9 For instrument operations, provide a functional description of operational modes, and ground and on-orbit calibration schemes. This can be documented in Mission and Operations Section. Describe the level of complexity associated with analyzing the data to achieve the scientific objectives of the investigation. Describe the types of data (e.g. bits, images) and provide an estimate of the total data volume returned.

Details about the Instrument operation modes, calibration schemes and data processing can be found in Section 3.10 and Section 7 of this RFI Part-2 and the following documents:

- Section "2. Technical Overview" of the SIM Lite Astro2010 RFI Part 1,
- The SIM Lite Book [Davidson/2009], especially chapter 17, http://sim.jpl.nasa.gov */Key Published Papers/2009 SIM Book*

The primary data used for science come from the interferometer fringe tracking cameras, the Guide 2 telescope camera, and the metrology system. The data coming from the interferometer fringe tracking cameras can be converted into optical delay (i.e. one dimension measurements of the position of the star of interest relative to fiducials in the instrument). The data coming from the metrology sensors are a series of one-dimensional measurements of the relative positions of fiducials in the instrument. By combining optical delays, metrology measurement and star geometry from multiple observations, the astrometric position of the various stars of interest can be solved for.

The instrument science sensors generate about 6300 kbits per second during observation, mainly driven by on-orbit real-time control needs. The Instrument control electronics then compresses the science data volume on-board (by simple averaging operations) down to 40 kbits per second. In addition, about 60 kbits per seconds of engineering data is produced. Overall, the instrument generates 56 Gbits per week of data to be returned to the ground to solve for the astrometric positions.

3.10 Describe the instrument flight software, including an estimate of the number of lines of code.

The Instrument Flight Software is responsible for coordinating the flight computer and electronics and reading sensor data, executing control loops, and commanding actuators such that the required picometer level science data can be extracted on the ground. The Flight Software architecture consists of a layered architecture where only communication between the connected layers is encouraged. Encapsulation layers are created to isolate the application from a specific operating system and device hardware protocol. Each layer has objects that respond to requests from above and levy requests on objects in layers below. Object-oriented design philosophy (C++) is utilized within these layers to maximize cohesion within an object and minimize the coupling between objects.

Table 3.10-1: SIM Lite Instrument Software Lines of Code Estimate

Software Item Description	Lines of Code
Supervisory layer: • Executive • Configuation Handler • Telemetry Handler • Data Handler • Fault Protection Handler • Command Handler • Framework	20,300
Instrument Control layer: • Instrument Mode Control	1,000
Functional Mode Control layer: • Guide Functional Mode Control • Science Functional Mode Control • Estimator Functional Mode Control	2,400
Algorithms layer: • Angle Estimator and Controller • Fringe Estimator and Controller • Instrument Attitude Estimator • Instrument Pathlength Estimator • Math Libraries	7,000
Device Manager layer: • Fringe Tracking Camera & Processing Device Manager • Angle Tracking Camera & Processing Device Manager • Metrology Phase-Meter Device Manager • Pathlength Mechanism Device Manager • Pointing Mechanism Device Manager	5,300
Transport Driver layer: • Solid State Recorder Driver • Non-Volatile Memory Driver • Serial Bus Driver • Serial Point-to-Point Communication Driver	6,000
Total:	**42,000**

The Supervisory layer provides commanding, scheduling, telemetry, fault protection reporting and configuration capabilities. The Instrument Control layer houses the Instrument Mode Controller module. This layer is responsible for controlling the highest-level modes for the instrument real-time control system. The Functional Mode Control layer houses the modules responsible for controlling various high level functions – Guide interferometer, Science interferometer and Instrument estimator. The Algorithm layer houses the control modules that are responsible for coordinating all activities between the hardware devices and the real-time control. These control modules provide wrappers around the delivered algorithms and are responsible for coordinating all command and control between algorithms, hardware managers and the communication of status back to the Functional Mode Control layer. The Device Managers layer houses all the actuator and sensor manager modules that are responsible for managing the state of a device. These modules provide capabilities for sending commands and receiving status and sensor information to the Algorithm layer above. The Transport Drivers layer houses all the modules responsible for communicating across the direct physical interfaces such as the 1553 bus, the point-to-point serial links and the Non-Volatile Memory.

The number of lines of C++ code to be developed for the SIM Lite instrument has been estimated based on flight code developed at JPL for avionics on other spacecraft, experience with the real-time control software developed for the SIM technology testbeds, and algorithms developed for the instrument control simulations. The Line of Code estimate is provided in the Figure 3.10-1.

There are six Instrument Modes: Startup, Idle, Checkout, Diagnostic, Observing, and Safe. These are listed briefly below. Note that there is a vast amount of detail below this level that there isn't space in this document to include.

1. Startup: All functions necessary to prepare the instrument for transition to the Idle mode.
2. Idle: The standby state of the instrument.
3. Checkout: Configures the instrument for self-checks. Returns to Idle mode upon exit.
4. Diagnostic: Special mode for troubleshooting. Returns to Idle mode upon exit.
5. Observing: This is the normal instrument operational mode. Returns to Idle mode upon exit.
6. Safe: Places the instrument in a safe configuration.

3.11 Describe any instrumentation or science implementation that requires non-US participation for mission success.

Not applicable. The SIM instrument will be fully developed in the US.

3.12 Please provide a detailed Master Equipment List (MEL) for the payload sub-categorized by each specific instrument indicating mass and power of each component. This table will not be counted in the page totals.

See Table 3.12-1, SIM Lite Instrument MEL, part 2, with Mass and Power.

3.13 Describe the flight heritage of the instruments and its subsystems. Indicate items that are to be developed, as well as any existing hardware or design/flight heritage. Discuss the steps needed for space qualification.

Table 3.13-1, SIM Lite Instrument MEL Part 3: with Space Qualification approach provided, shows the list of assemblies that form the SIM-Lite instrument. For each assembly, the TRL level is provided, the hardware already developed during the phase A-B, mainly bread-board (bb) or Brass-Board (BB) models. The table also provides the expected hardware to be developed during the implementation phase for the flight system.

In most cases, proto-flight unit builds are planned when the engineering risk was already retired through successful Brass-Board implementation. For large structures, proto-flight units will also be built. In the rest of the cases, Engineering Models will be built for qualification followed by Flight unit builds.

Table 3.2-1: SIM Lite Instrument MEL, Part 1, with Technology Readiness Level and Basis

Master Equipment List item	TRL	Basis
SIM-Lite Instrument Total	6	Performance testing of all major subsystems of the instrument using bb or BB hardware.
Collector Sub-system	6	Thermal performance testing of BB collector telescope. Performance testing of bb mechanisms and metrology components in SIM-like interferometer.
Collector Optical Bench Structure		No new technology
Collector Truss Structure		No new technology
Siderostat Mechansim	5	Environmental and performance test of BB siderostat, encoder not yet space-qualifed
Primary mirror Assy	6	Environmental and performance test of BB unit
M2 Assembly		No new technology
Long Stroke Optical Delay Line	5	Similar BB delay-line was qualified
Fixed Optical Delay Line		No new technology
Short Optical Delay Line	6	Similar design as the Alignment mechanism
Modulation Optical Mechanism	6	Environmental and performance test of BB unit
Alignment mechanism	6	Environmental and performance test of BB unit
Fine Steering Mirror Assembly	6	Environmental and performance test of BB unit
Pupil Mask Assembly		No new technology
Relay Optics Mount Assemblies		No new technology
Triple Corner Cube Support	5	EM TCC will be build to mitigate this risk
DCC, ACC, CCC Corner-Cubes	6	Environmental and performance test of BB DCC
TCC Translator Mechanism		No new technology
Xmet Beam Launchers	6	Environmental and performance test of BB unit
Guide 2 telescope Back-end	6	Reuse ABC sub-assembly design.
Astrometric Beam Combiner Sub-system	6	Thermal performance testing of BB Astrometric Beam Combiner in SIM-like interferometer with Camera cooling.
Astrometric Beam Combiner	6	Environmental and performance test of BB unit
Cold Camera Cooling		No new technology
ABC Main Support Structure		No new technology
ABC Support Truss		No new technology
Precision Structure Subsystem	6	Thermal performance testing of one BB strut of the Precision Structure.
Precision Structure		No new technology
Deployable Contamination Cover		No new technology
PAF Separation Nut Assembly		No new technology
Solar Array tie-down		No new technology

Metrology source Subsystem	6	Performance testing of bb of the metrology source driving a SIM-like metrology truss
Metrology Source Optical Bench	5	Environmental and performance test of a similar BB metrology bench
Acousto-Opto-Modulators	5	Need to be life-tested
Pump Diode Modules	5	Need to be life-tested
Optical Frequency Counters		No new technology
RF Drive Electronics Modules		No new technology
Fiber Distribution Assembly	6	Environmental and performance test of BB unit of the longest (most complex) path of the distribution system
Source Radiator		No new technology
Control Electronics Equipment	6	Performance testing bb of full instrument system with SIM-Like 3 baseline interferometer and metrology system
Instrument Compartment Structure		No new technology
Collector Electronics Boxes		No new technology
ABC Electronics Boxes		No new technology
Metrology Beam Launcher Electronics	5	Performance test of bb unit
Commander Electronics Box		No new technology
Instrument Control Computer Box		No new technology
Strain Gauge dog house	5	Performance test of bb unit
Metrology postamp dog house	5	Performance test of bb unit
Remote Engineering Units		No new technology
Camera Doghouse	6	Environmental and performance test of BB unit
System		
Cable Trays		No new technology
System Cabling		No new technology
Thermistor		No new technology
Heaters		No new technology
Thermal Blanket Supports		No new technology
Thermal Blankets		No new technology

bb - bread-board model BB - Brass-Board model EM – Engineering Model

Table 3.12-1: SIM Lite Instrument MEL, Part 2, with Mass & Power

Mass and power including contingency	Number of Assy	Mass (kg)		Power (W)	
		System Mass	Mass per Assy	System Power	Power per Assy
SIM-Lite Instrument Total		**2,825**	**kg**	**2,450**	**W**
Collector Sub-system		**1,198**	**kg**	**1,234**	**W**
Science Collector Optical Bench Structure	2		52.3		182.0
Guide Collector Optical Bench Structure	2		40.3		112.0
Collector Truss	1		113.0		168.0
Science Siderostat Mechanism	2		202.3		134.4
Guide Siderostat Mechanism	1		77.3		42.0
Science M1 Mirror Assembly	2		33.5		
Guide M1 Mirror Assembly	2		20.5		
M2 Mirror Assembly	4		1.0		
Long Stroke Optical Delay Line Mechanism	2		10.0		7.0
Fixed Optical Delay Line Assembly	2		3.4		
Short Optical Delay Line Mechanism	1		1.1		0.7
Modulation Optical Mechanism	4		2.1		
Alignment Mirror Mechanism	3		1.8		1.4
Fine Steering Mirror Mechanism	4		1.5		
Pupil Mask Translation Mechanism	4		1.2		1.4
Relay Mirror Assembly	4		0.8		
Triple Corner Cube Assembly	2		3.6		14.0
ACC and CCC Corner Cube Assembly	2		2.8		
TCC Translation Mechanism	1		9.7		2.8
Ext. Metrology Beam Launcher Assembly	10		7.0		7.0
Guide 2 Telescope Back-End Assembly	1		13.7		42.0
Collector Cabling	4		30.0		
Thermal Blankets	4		6.0		
ABC Sub-system		**314**	**kg**	**196**	**W**
Astrometric Beam Combiner (ABC) Assembly	2		79.8		22.4
Cold Camera Cooling Assembly	1		22.2		
ABC Main Support Structure	1		67.7		109.0
ABC Support Truss	1		13.6		42.0
ABC Cabling	2		21.0		
Thermal Blankets	1		8.8		
Precision Structure Subsystem		**849**	**kg**	**309**	**W**
Precision Structure	1		530.4		
Deployable Contamination Cover	2		18.8		
PAF Separation Nut Assembly	4		11.7		
Solar Array tie-down	1		19.5		
Thermal blankets	1		79.3		
Thermal Blanket Supports	1		6.5		
Heaters	1		33.8		309.0
Thermistor	1		1.3		
Electrical Cables	1		65.0		
Cable Trays	1		28.8		
Metrology source Subsystem		**69**	**kg**	**206**	**W**
Metrology Source Optical Bench Assembly	1		0.0		28.0
Laser Pump Diode Modules	2		6.4		17.4
Optical Frequency Counters	1		6.0		14.0
RF Drive Electronics	1		12.1		30.8
Fiber Distribution Assembly	1		12.3		84.0
Fiber Splitter Box Assembly	1		8.1		14.0
Source Electrical Cables	1		3.4		
Source Radiator	1		12.0		
Thermal Blankets	1		2.5		
Control Electronics Equipment		**395**	**kg**	**506**	**W**
Instrument Compartment Structure	1		45.0		
Collector Electronics Boxes	4		12.5		49.0
ABC Electronics Boxes	2		12.2		39.2
Beam Launcher Electronics Box	1		20.8		98.0
Commander Electronics Box	1		13.3		49.0
Instrument Control Computer Box	1		14.3		58.8
Strain Gauge dog house	4		2.1		0.4
Metrology postamp dog house	14		4.2		0.8
Remote Engineering Units	6		2.1		0.4
Camera Doghouse	5		3.6		2.1
System Cabling	1		130.0		

Table 3.13-1: SIM Lite Instrument MEL, Part 3, with Space Qualification approach indicated.

Master Equipment List Item	TRL	Phase A-B		Phase C-D		
		Performance test with bb unit	Envir. & Perf. test with BB unit	EM/Qual units	Proto-flight units	Flight units
Collector Sub-system						
Collector Optical Bench Structure		x			4	
Collector Truss Assembly					4	
Science Siderostat		x		1		2
Guide Siderostat			x		1	
Science Primary mirror				1		2
Guide Primary mirror			x		3	
M2 Assy		x			5	
Long Stroke Optical Delay Line		x		1		2
Fixed Optical Delay Line					2	
Short Optical Delay Line				1		1
Modulation Optical Mechanism			x		4	
Alignment mechanism			x		3	
Fine Steering Mirror mechanism			x		4	
Pupil Mask mechanism				1		4
Relay Optics Mount					4	
Triple Corner Cube Support				1		2
DCC, ACC, CCC Corner-Cubes			x	1 *	2 *	2 *
TCC Translator Mechanism				1		1
Xmet Beam Launcher			x	1		10
Guide 2 telescope Back-end			x		1	
ABC Sub-system						
Astrometric Beam Combiner (ABC)			x		2	
Cold Camera Cooling			x		1	
ABC Main Support Structure					1	
ABC Support Truss					1	
Precision Structure Subsystem						
Precision Structure			x **		1	
Deployable Contamination Cover				1		2
PAF Separation Nut Assembly				1		4
Solar Array tie-down					1	
Metrology source Subsystem						
Metrology Source Optical Bench			x **	1		1
Acousto-Opto-Modulators		x		1		4
Pump Diode Modules		x		1		2
Optical Frequency Counters		x			1	

MEL Tables. No page count.

RF Drive Electronics Modules		x			1	
Fiber Distribution Assembly			x **		1	
Source Radiator					1	
Control Electronics Equipment						
Instrument Compartment Structure					1	
Collector Electronics Boxes		x		1 **		4
ABC Electronics Boxes		x		1 **		2
Metrology Launcher Electronics		x		1 **		1
Commander Electronics Box		x		1 **		1
Instrument Control Computer Box		x		1		1
Strain Gauge dog house		x		1		4
Metrology postamp dog house		x		1		14
Remote Engineering Units				1		6
Camera Doghouse		x		1		5
System						
Cable Trays					1	
System Cabling					1	
Thermistor					1	
Heaters					1	
Thermal Blanket Supports					1	
Thermal Blankets					1	

bb - bread-board model BB - Brass-Board model

* (1) EM and (2) Flight DCC, (1) Proto-flight ACC, (1) Proto-flight CCC

** BB of one representative part of the full assembly

*** EM Qualification at the board level

Table 3.4-1: SIM Lite Instrument Table

Item	Value	Units
Type of instrument	Optical	
Number of channels	80	Spectral channels
Size/dimensions (for each instrument)	7.4 x 2.8 x 1.9	m x m x m
Instrument mass **without** contingency (CBE*)	2,156	Kg
Instrument mass contingency	31	%
Instrument mass **with** contingency (CBE+contingency)	2,825	Kg
Instrument average payload power **without** contingency	1,866	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	2,426	W
Instrument average science data rate^ **without** contingency	4400	kbps
Instrument average science data^ rate contingency	43	%
Instrument average science data^ rate **with** contingency	6300	kbps
Instrument Fields of View (if appropriate)	0.011	degrees
Pointing requirements (knowledge)	0.000,833	degrees
Pointing requirements (control)	0.000,278	degrees
Pointing requirements (stability)	0.000,000,74	deg/sec

*CBE = Current Best Estimate.

^Instrument data rate defined as science data rate prior to on-board processing.

Table 3.6-1: SIM Lite Payload Mass Table (kg)

	Current Best Estimate (CBE)	**Percent Mass Contingency**	**CBE Plus Contingency (kg)**
SIM Lite Instrument	2,156	31%	2,826
Total Payload Mass	2,156	31%	2,826

SIM Lite Payload Power Table (W)

	Current Best Estimate (CBE)	**Percent Power Contingency**	**CBE Plus Contingency (W)**
SIM Lite Instrument	1,866	30%	2,426
Total Payload Mass	1,866	30%	2,426

Note: Contingencies calculated consistent with JPL’s Design, Verification/Validation and Operations Principles for Flight Systems (Design Principles), Rev. 3. See the note below Table 4.3-1 for details of these calculations.

4 Technical Implementation – Mission Design

There is a lot of very detailed information on SIM Lite. The answers to the questions below should be read in conjunction with the SIM Lite Book (Davidson/2009), available on the SIM Lite website at http://sim.jpl.nasa.gov */Key Published Papers /2009 SIM Book.*

4.1 Provide a brief descriptive overview of the mission design (launch, launch vehicle, orbit, pointing strategy) and how it achieves the science requirements (e.g. if you need to cover the entire sky, how is it achieved?).

The Space Interferometry Mission Lite (SIM Lite) flight system, consisting of a spacecraft and interferometer instrument, will be launched into orbit from the Eastern Test Range at the Cape Canaveral Air Station. SIM Lite will be placed into in the same Earth-trailing solar orbit (ETSO) as were Spitzer and Kepler by an intermediate-class Evolved Expendable Launch Vehicle (EELV). The 2,980 kg current best estimate (3,827 kg including mass contingency) of the SIM Lite **wet** mass results in a launch vehicle mass margin of 33%. 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 5.5 years. This orbit also enables one of the science experiments for SIM Lite, namely the gravitational microlensing experiment, that would not be possible from an L2 orbit.

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 five years, performing nearly continuous science observations over the entire celestial sphere. Separate, interleaved Wide-angle and Narrow-angle campaigns occur throughout the mission.

The SIM Lite science interferometer makes measurements of the path delay (through the instrument) of stars observed sequentially. These measurements can be processed to represent angles on the sky 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 the prior measurement. Since the orientation of the baseline may be determined by many factors, the operations do not require that the nominally orthogonal observations be paired up nor must the position angles be repeated.

Both during and between measurements, the science interferometer is held stable by continuous observations of known, bright stars (referred to as “guide” stars) through the guide interferometer and telescope. The guide interferometer observes a bright star in approximately the same direction as the science target. The Guide-2 telescope observes a second guide star, roughly orthogonal to the first. These two instruments observe continuously during a set of observations, sensing the pointing of the spacecraft and providing corrections to the pointing and delay of the science instrument. All SIM Lite astrometric measurements are made within the framework of a basic unit of observation called a “tile”. Individual stars are observed within a “tile” 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 into campaigns of tiles. The slew to a tile is done under the control of the spacecraft using reaction wheels and a conventional star tracker. Small reaction control thrusters are used for desaturation of reaction wheels. During slews, the science interferometer, guide interferometer, and Guide-2 telescopes are not taking data. They can, however, be pre-positioned to minimize the acquisition time once they become active. Once in position, the spacecraft bus provides the coarse-level pointing of 5 arcseconds (3 sigma), pointing stability of 0.2 arcseconds over 100 seconds and 0.02 arcseconds over 1 second. The SIM Lite instrument will ultimately provide the micro-arcsecond pointing and stability needed for astrometric observations. In this way, the science interferometer can be regarded as inertially fixed, to a precision better than the individual measurements, during and between science measurements.

As mentioned above, the tile is defined as the set of observations performed while the guide interferometer and Guide-2 telescope remain "locked" onto guide stars. 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. The narrow-angle (NA) observing scenario is used for the astrometric search for exoplanets and other investigations requiring the utmost performance of SIM Lite. A more detailed description of the SIM Lite observing strategy for all of the science campaigns can be found in Chapter 17 (*Observing with SIM Lite*), http://planetquest.jpl.nasa.gov/SIM/files/Chapter-17-LR.pdf of the SIM Lite book (http://planetquest.jpl.nasa.gov/SIM/files/SIM-Book-Full-Book-LR.pdf).

Individuals and science teams wishing to obtain astrometric measurements from SIM Lite will begin the process well before launch. Working with the NASA Exoplanet Science Institute (NExScI), investigators will use estimation software to determine the number and frequency of measurements of this targets for the precision desired and submit their full sets for the mission to NExScI. NExScI will prepare a five-year schedule of observations, fitting observations requests, spacecraft maintenance, data downlinks, calibrations, and other flight activities into the schedule.

Science and engineering data will be recorded onboard and downloaded during tracking sessions using DSN 34 m ground antennas. Frequency and duration of the Ka-band HGA downlink sessions will be no more than eight hours per week (end of mission).

Sixteen hours of Doppler ranging will be provided each week to determine the SIM Lite position to within 50 km and velocity to within 2 cm/sec. This can occur over the Ka-band circuit during data downlink or over the omni-directional X-band low gain antenna when not down-linking data.

4.2 Describe all mission software development, ground station development and any science development required during Phases B and C/D.

The SIM Lite Instrument and Spacecraft operations centers will be located at JPL.

The SIM Lite mission operations ground data system (GDS) will use JPL's Advanced Multi-mission Operations System (AMMOS) with no modifications. Command and Telemetry dictionaries will be developed during Phase C for use during Mission I&T and Operations.

The SIM Lite Science Operations System (SOS) must complete the tools that support the General Observer proposal process, administer the proposal process, support the finalization of the observation strategy for the selected proposals and develop the scheduling system and the entire observing schedule prior to launch. In addition, the data processing system needs to be functionally complete early enough to support processing of test data during ATLO. The data processing system needs to be good enough at the time of launch to support processing and analysis of the data quality during IOC.

No DSN software development is required to support SIM Lite.

4.3 Provide entries in the mission design table. For mass and power, provide contingency if it has been allocated. If not, use 30% contingency. To calculate margin, take the difference between the maximum possible value (e.g. launch vehicle capability) and the maximum expected value (CBE plus contingency).

See Table 4.3-1. Note that we have interpreted "spacecraft" to mean the entire satellite and have changed the row labels in the table to reflect this. Also see the JPL contingency definitions that were used, in the note below Table 4.3-1.

4.4 Provide diagrams or drawings showing the observatory (payload and s/c) with the instruments and other components labeled and a descriptive caption. Provide a diagram of the observatory in the launch vehicle fairing indicating clearance.

See Figures 4.4-1 and 4.4-2, below.

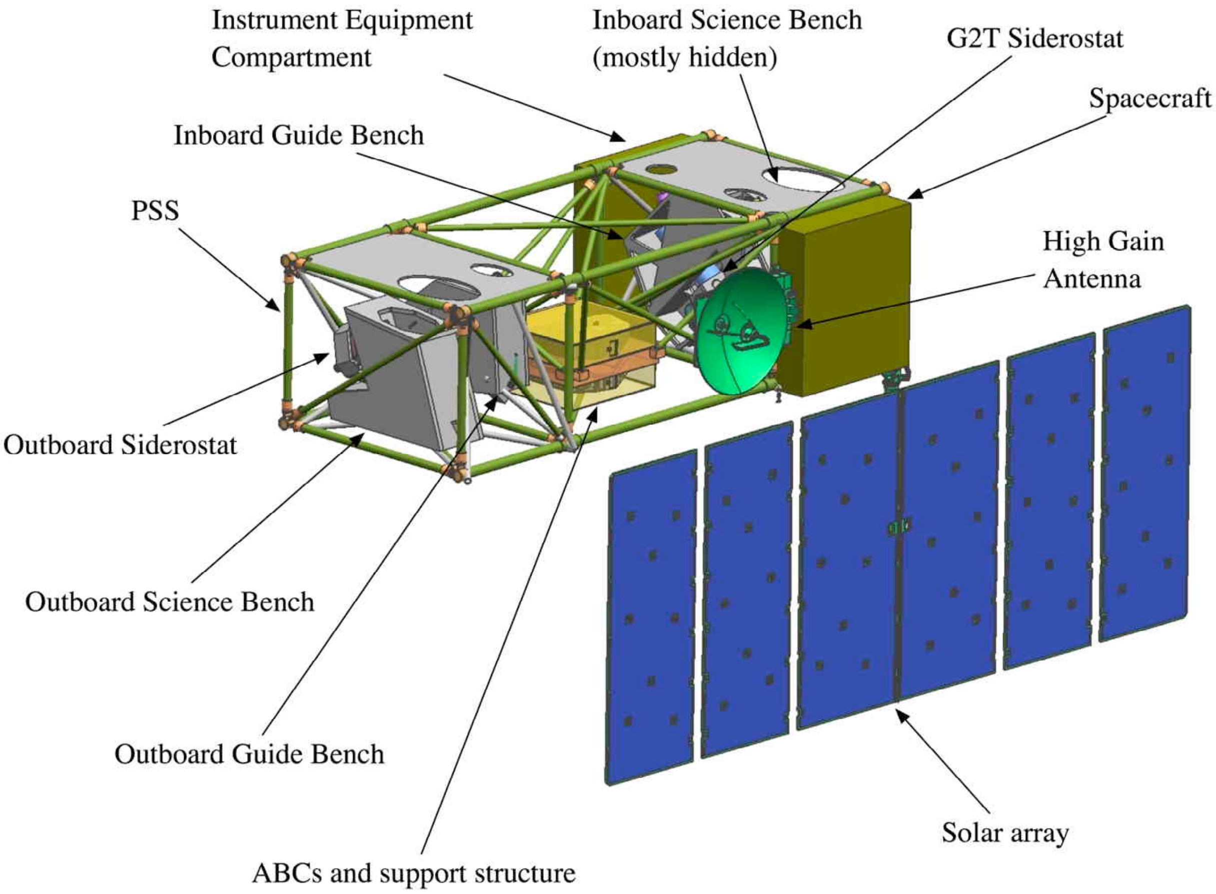


Figure 4.4-1: Observatory payload and Spacecraft. Note that the payload consists of everything except the spacecraft bus mounted on one side of the instrument precision structure. Both the spacecraft bus and the Instrument precision structure are free to expand along the long axis of the instrument, although, packaging studies indicate that this will not be required. PSS = Precision Structure Subsystem; G2T = Guide 2 Telescope; ABC = Astrometric Beam Combiner (2, one for each Michelson Stellar Interferometer).

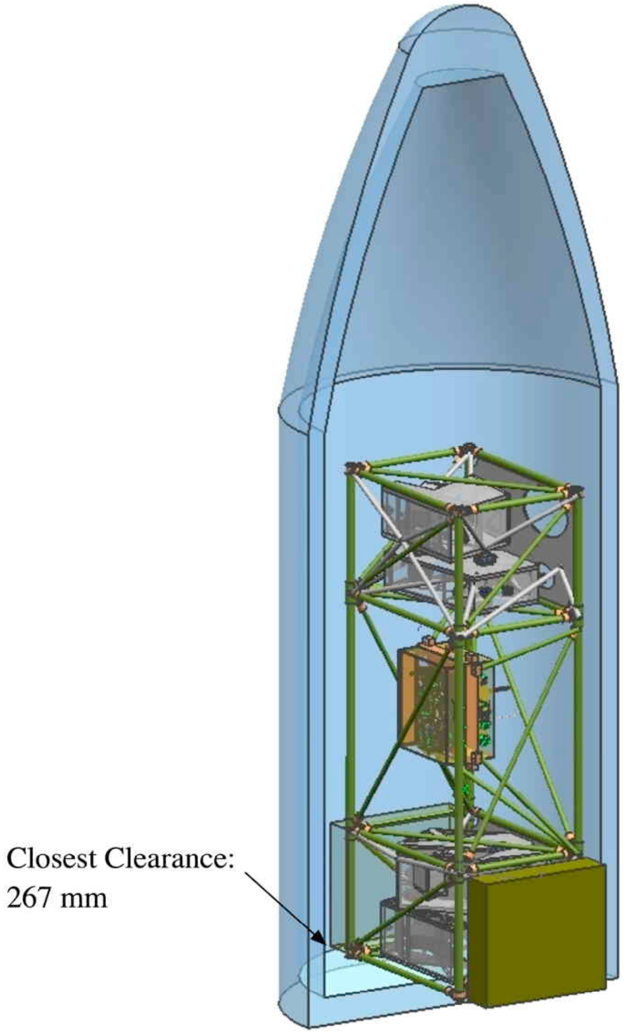


Figure 4.4-2: SIM Lite Observatory in the launch vehicle faring. The clearance shown is between the flight system and the dynamic envelope. If additional volume is required for either the Instrument Electronics or the Spacecraft bus, both can expand along the long axis of the instrument, although detailed layout studies indicate that this will not be necessary.

4.5 For the mission, what are the three primary risks?

4.5.1 Potential ELV Cost Increase: If the competitive environment for EELVs changes for any of a number of reasons, then the cost to SIM for these launch vehicles could significantly change (up/down).

4.5.2 Resource Impact of Potential SIM Lite Instrument Redundancy/Reliability Architecture: The SIM Lite mission redesign has used an Instrument redundancy architecture consistent with the 2005 SIM Redesign and other observatories. Should a more conservative approach be mandated at some future time, mass and cost could increase.

4.5.3 Spacecraft Development Lag: The phase B funding constraints and priorities between Instrument and spacecraft (S/C) schedules may result in the Instrument being further along in the design and development process than the S/C. If interface problems develop during the detailed design phase, then it is likely that the S/C will have to accommodate the design changes necessary to eliminate these problems.

Table 4.3-1: Mission Design Table (Note: Satellite Mass & Power includes Payload)

Parameter	Value	Units
Orbit Parameters (apogee, perigee, inclination, etc.)	Heliocentric	
Mission Lifetime	64	mos
Maximum Eclipse Period	NA	min
Launch Site	KSC	
Satellite Dry Bus Mass **without** contingency	2940	kg
Satellite Dry Bus Mass contingency	27	%
Satellite Dry Bus Mass **with** contingency	3730	kg
Satellite Propellant Mass **without** contingency	40	kg
Satellite Propellant contingency	140	%
Satellite Propellant Mass **with** contingency	97	kg
Launch Vehicle	Atlas V (521)	Type
Launch Vehicle Mass Margin	1475*	kg
Launch Vehicle Mass Margin (%)	33*	%
Satellite Bus Power **without** contingency	2770	W
Satellite Bus Power contingency	21	%
Satellite Bus Power **with** contingency	3360	W

*NOTE: Mass margins were calculated as required in JPL's Design, Verification/Validation & Ops Principles for Flight Systems (Design Principles), Rev. 3. This document states that margins shall be calculated per the following:

6.3.2 System Mass Margins

6.3.2.1 System dry mass margin definitions - The below definitions shall be used for determining system dry mass margins.

Dry Mass Margin = Dry Mass Allocation - Dry Mass Current Best Estimate (CBE)

% Dry Mass Margin = 100% * (Dry Mass Margin/Dry Mass Allocation)

Note: Dry Mass Allocation is defined relative to the launch vehicle payload allocation, as follows:

Dry Mass Allocation = L/V Payload Allocation - Mass of S/C Propellant(s)

Note: Uncertainty in the L/V payload lift capability may be reason to derate the L/V Payload Allocation. Discussion with the L/V provider for who is to carry the reserve against L/V performance shortfalls serves as a guide in this regard.

Note: Dry Mass CBE is the best estimate taking into account everything known, but exclusive of the growth that likely will occur based on maturity.

Note: Dry mass includes any ballast mass(es) for CG control of the fueled s/c.

5 Technical Implementation – Spacecraft Implementation

5.1 Describe the spacecraft characteristics and Requirements. Include a preliminary description of the spacecraft design and a summary of the estimated performance of the key spacecraft subsystems. Please fill out the Spacecraft Mass Table.

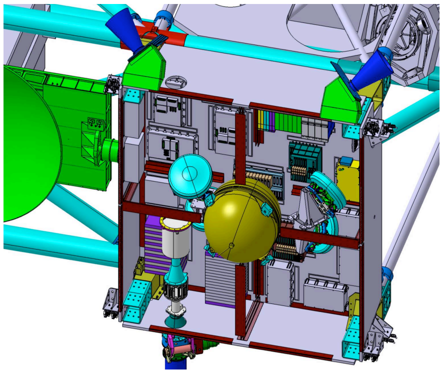


Figure 5.1-1: The SIM Lite spacecraft is based on high heritage components and flight proven design concepts (facing close-out panel not shown).

The SIM Lite spacecraft, Figure 5.1-1 and mass Table 5.1-1, 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 spacecraft structure is a 195 x 210 x 60 cm graphite honeycomb structure in the shape of a closed box braced by an internal cruciform structure. It houses the propellant tank and other spacecraft components.

The Attitude Control Subsystem (ACS) provides space vehicle maneuvering to position the instrument with knowledge of less than 5 arcsecond (3 sigma) and stability of less than 0.2 arcsecond/100sec/axis (3 sigma) to support the science mission. Momentum unloading is achieved via six Northrop Grumman dual thruster mono propellant modules.

The redundant Command and Data Handling subsystem uses a Rad750 processor board with 36 MB of RAM to host the flight software and control the spacecraft. The 96 Gb (single side) on-board data storage system is almost twice the required 50 Gbits/week memory for science data.

Communication is via X-band low-gain omni-directional antennas for both up and down link for command and telemetry. Science data is down-linked using the Ka-band high gain body-steered antenna. No science operations will be scheduled during science down links, as the spacecraft needs to point the high gain antenna at Earth during this time. Doppler ranging will be performed via the X up/down or X up/Ka Down links. Differential one-way (DOR) ranging is also supported via X- or Ka-bands.

Spacecraft power is provided via a single-wing 16.6m^2 dual-gimbaled triple-junction GaAs solar array and Saft Lithium ion batteries. The 96 Ah battery's main function is to provide power during launch and from launch vehicle separation to solar array deployment with some capability during safe modes.

5.2 Provide a brief description and an overall assessment of the technical maturity of the spacecraft subsystems and critical components. Provide TRL levels of key units. In particular, identify any required new technologies or developments or open implementation issues.

The spacecraft uses Northrop Grumman heritage components and flight proven designs with minor, incremental improvements in performance. All components are at least TRL 6.

5.3 Identify and describe the three lowest TRL units, state the TRL level and explain how and when these units will reach TRL 6.

All subsystem components have a TRL 6 or higher implementation that meets the SIM Lite requirements. In some subsystems, further performance improvements are expected prior to PDR. For example, the dual stage reaction wheel isolator, Figure 5.3-1, is a refinement of the flight proven Chandra units. It nevertheless needs further development to fine-tune it to the SIM Lite requirements, as it would for any mission other than Chandra. The basic components of the dual stage isolator are at or above TRL6.

5.4 What are the three greatest risks with the S/C?

During the independent cost estimate in early 2009, the Aerospace Corporation identified the relatively high bus density as the only spacecraft related risk. Their concern was that the high packaging density would allow for little growth in component volume and might result in tight cable and harness runs. We have since studied two possible mitigations: As recommended by Aerospace Corporation, we performed detailed modeling of the component layout including harness runs. Currently we can accommodate all components with sufficient clearance to integrate harnesses and have margin for some growth. Further component growth can be accommodated by increasing the dimensions of the spacecraft structure along the long axis of the instrument.

5.5 If you have required new S/C technologies, developments or open issues, describe the plans to address them (to answer, you may provide technology implementation plan reports or concept study reports).

The SIM Lite spacecraft does not require new technologies.

5.6 Describe subsystem characteristics and requirements to the extent possible. Describe in more detail those subsystems that are less mature or have driving requirements for mission success. Such characteristics include: mass, volume, and power; pointing knowledge and accuracy; data rates; and a summary of margins. Comment on how these mass and power numbers relate to existing technology and what light weighting or power reduction is required to achieve your goals.

All subsystems of the SIM Lite spacecraft are within the current state of the art. Graphite composite spacecraft structure for reduced mass and Gallium Arsenide solar arrays for increased efficiency.

The Structures and Mechanisms Subsystem is responsible for the design, analysis, fabrication and structural testing of spacecraft mechanical hardware including the bus, High Gain Antenna (HGA), Low Gain Antenna support structures, as well as the solar array mechanical design, analysis, fabrication and testing (panels, booms, hinges). The spacecraft bus is a closed box design, braced by an internal cruciform structure connecting to a cylindrical support for the propellant tank, consisting of honeycomb panels and Resin Transfer Molded (RTM) frame members. The solar array structure is based on the GeoLite design and consists of four graphite honeycomb panels and deployed via motorized boom deployment. Six tape hinges provide panel to panel deployment of the solar array.

The SIM Lite Propulsion Subsystem provides for nulling launch vehicle tip-off rates, initial sun acquisition after solar array deployment, periodic unloading of angular momentum, and sun acquisition after a spacecraft fault. The Propulsion Subsystem design is an all-welded monopropellant hydrazine blow down Reaction Control System. Impulse is provided by catalytic decomposition of hydrazine stored in the propellant tank and supplied to the thrusters in a blow-down pressurization mode. Twelve 4.45N (1.0lbf) thrusters are packaged in six dual thruster modules. Each individual thruster uses a normally closed hydrazine propellant thruster valve to provide for positive on-off flow control for hydrazine. The propellant tank is a cylindrical titanium tank with hemispherical heads and elastometric diaphragm. All propulsion components have high heritage and have been used on the EOS and Chandra programs.

The Thermal Control Subsystem uses Annealed Pyrolytic Graphite (APG) doublers for spreading the heat. Aluminized Kapton MLI is use for the bus compartment, IRU, star trackers, and solar array drives. Fused silica second surfaced mirror radiators on the bus panels and star trackers are used for heat rejection. Heaters are controlled by mechanical thermostats to maintain bus mounted equipment and appendages minimum temperatures. Heaters are controlled by mechanical thermostats and MLI to maintain propulsion equipment temperatures.

The primary function of the Power Subsystem is to generate and distribute conditioned electrical power to the spacecraft and the payload during all phases over the mission life of the space vehicle. During the ascent phase after launch vehicle separation and until Sun acquisition power is provided by the lithium ion batteries. Thereafter, primary DC power generation is provided by the 3.3 kW (End-of-Life at 1.1 AU) dual gimbaled solar array. Solar array margin is 2.6% at EOL and battery maximum Depth of Discharge (DOD) is 60% with one cell string failed. Spacecraft heaters are controlled by mechanical thermostats and power is provided for instrument heaters through the spacecraft to instrument interface. The EOL capacity of the power system includes a 30 percent contingency on the current best estimate of the payload power.

The Avionics Subsystem is responsible for the development of the Flight Computer, composed of the Spacecraft Control Processor (SCP) that is the data processing facility that hosts the flight software. It manages the spacecraft hardware assemblies and safe operation, supports autonomous operations and fault protection, processes uplink commands and provides downlink science and telemetry through the telecomm subsystem to ground operations. It controls and monitors the instrument system and spacecraft through its spacecraft data buses.

The Spacecraft Control Processor consists of a Rad750 Processor Board plus 36MB of RAM for controlling the spacecraft and application flight software. Two mass memory boards are included for record/playback mission and science data. The Avionics Subsystem is single fault tolerant implemented in dual string architecture. It includes a maximum of 10 days of autonomous operation, including safe mode. Mass memory requirements are met by providing 4 high-speed ports at up to 8.125 Mbps per port with a maximum of 50 Gb of weekly science data.

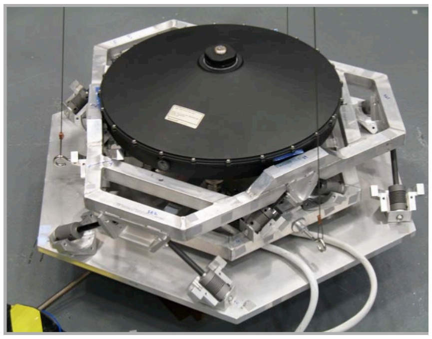


Figure 5.3-1: The dual stage isolator, here shown with a Honeywell RWA, is a refinement of the reaction wheel isolators used on Chandra.

The Telecomm Subsystem consists of an X-band command uplink and X-band telemetry and Ka-band sciences data downlinks for communications with the Deep Space Network. The X-band downlink via the HGA also supports science data if required. The downlinks have concatenated Reed Solomon (RS) and Convolutional coding. A body mounted high gain antenna transmits both X and Ka-bands and receives in X-band. The Ka-band downlink can transmit up to 6.4 Mbps of mission data (50 Gb of data within 2.2 hours). The two low gain antennas provide near 4π steradian coverage for real-time telemetry and command as well as for support of anomaly resolution.

The Attitude Control System provides 3-axis attitude determination with star trackers and an IRU. Attitude control and knowledge is better than 5 arcsec (3 sigma). At the end of fine settle operation attitude stability is better than 0.2 arcsec/100s/axis (3 sigma). The spacecraft will complete a 7-degree slew in 4 minutes. The spacecraft has 120 seconds for settling after the slew. The ACS further ensures stable pointing of solar array and unloads stored momentum via 4.45-N (1.0 lbf) thrusters. During safing, the ACS controls the sun-pointed mode. The equipment has flown on EOS, Chandra and other missions.

Table 5.7-1 Spacecraft Heritage

Spacecraft Subsystem	Flight Heritage
Structures & Mechanisms	GeoLite and other missions
Thermal Control	EOS, NPOESS, other Northrop Grumman flown design concepts
Propulsion	EOS, Orbital Express
Attitude Control System	EOS, Chandra and other missions
Command & Data Handling	LCROSS
Telecommunications	NPOESS, restricted programs
Power	GeoLite, ATP (restricted)

With the exception of the coarse sun sensors all the ACS hardware connects to the flight computer via the 1553 data bus. The coarse sun sensor analog processor is connected directly to an analog to digital port on the SCP. All of the algorithms required to run the ACS subsystem reside in the SCP. Dual stage isolators reduce the jitter induced by the spacecraft reaction wheels below the levels required by the instrument payload.

5.7 Describe the flight heritage of the spacecraft and its subsystems. Indicate items that are to be developed, as well as any existing hardware or design/flight heritage. Discuss the steps needed for space qualification.

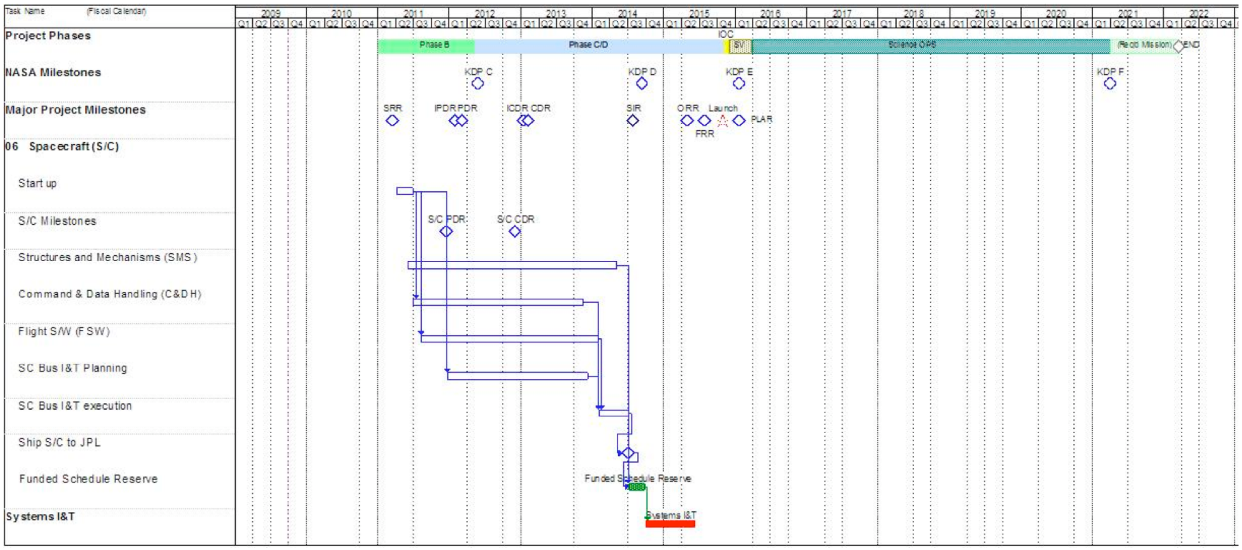
The spacecraft uses Northrop Grumman high heritage flight designs and flight proven components with some incremental performance improvement. Individual subsystems trace their flight heritage as shown in Table 5.7-1. Overall spacecraft heritage is estimated at 86 percent.

5.8 Address to the extent possible the accommodation of the science instruments by the spacecraft. In particular, identify any challenging or non-standard requirements (i.e., jitter/momentum considerations thermal environment/temperature limits, etc.).

The SIM Lite spacecraft is mounted on the side of the 7-meter long truss-based Precision Support Structure (PSS). The instrument subassemblies interface to the various nodes at the intersections of the PSS struts. No instrument components are housed inside or on the spacecraft compartment. The spacecraft compartment is mechanically and thermally isolated from the PSS. The reaction wheels inside the spacecraft are isolated via dual stage wheel isolators to reduce jitter below the instrument requirements.

5.9 Provide a schedule for the spacecraft, indicate the organization responsible and describe briefly past experience with similar spacecraft busses.

An overview of the 36-month SIM Lite spacecraft schedule is depicted below. The spacecraft will be developed and built by Northrop Grumman Aerospace Systems (NGAS). NGAS has recently completed the LCROSS spacecraft within 24 work months. NGAS will also draw on the experience with the similar NGAS developed GeoLite spacecraft.



5.10 Describe any instrumentation or spacecraft hardware that requires non-US participation for mission success.

The SIM Lite spacecraft and its subsystems do not require any non-US participation.

5.11 Fill out the Spacecraft Characteristics Table. See Table 5.11-1.

Table 5.1-1: Spacecraft Mass Table (kg)

Spacecraft bus	Current Best Estimate (CBE)	Percent Mass Contingency	CBE Plus Contingency (kg)
Structures & Mechanisms	202.7	20.0	243.2
Thermal Control	57.0	15.0	65.6
Propulsion (Dry Mass)	26.6	3.0	27.4
Attitude Control	140.0	14.8	160.7
Command & Data Handling	35.1	28.7	45.2
Telecommunications	41.4	11.2	46.0
Power	266.0	17.6	312.8
Total Spacecraft Dry Bus Mass	768.8	17.2	900.9

Table 5.11-1: Spacecraft Characteristics Table

Spacecraft bus	Value/ Summary, units
Structure	
Structures material (aluminum, exotic, composite, etc.)	Graphite composite
Number of articulated structures	1-solar array
Number of deployed structures	1-solar array
Thermal Control	
Type of thermal control used	Heaters
Propulsion	
Estimated delta-V budget, m/s	12 m/sec
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Mono- hydrazine
Number of thrusters and tanks	12 thrusters (in 6 modules), 1 tank
Specific impulse of each propulsion mode, seconds	213 sec
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb)	Earth trailing solar
Attitude control capability, degrees	.0014 deg (5 arcsec, 3 sigma)
Attitude knowledge limit, degrees	.0014 deg (5 arcsec, 3 sigma)
Agility requirements (maneuvers, scanning, etc.)	7 deg slew 4 min, 120 sec settling
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	Solar array 2 axis gimbal
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	momentum unloading via 4.45 N (1.0 lbf) thrusters
Command & Data Handling	
Spacecraft housekeeping data rate, kbps	8 kBps
Data storage capacity, Mbits	96000
Maximum storage record rate, kbps- uplink	4
Maximum storage playback rate, kbps- downlink	6400 BOL
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Deployed, articulated
Array size, meters x meters	16.6 m^2
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	Triple-junction GaAs
Expected power generation End of Life (EOL), watts	4,453W (EOL @ 0.95 AU) 3,319W (EOL @ 1.1 AU)
On-orbit average power consumption, watts	3,233W
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	96 Ah

Table. No page count.

6 Enabling Technology

Please update or provide information from the original RFI response describing new Enabling Technologies that must be developed for mission success. The committee assumes that Enabling Technology demonstrated by sub-unit demonstration models will be completed by the start of Phase-B. Technical Readiness of this demonstrated Enabling Technology at the full up unit level can occur after the start of Phase B during the Technical Implementation phase of the program. See the sections below. Please indicate any non-US technology that is required for mission success and what back up plans would be required if only US participation occurred.

Not Applicable. SIM has completed the Pre-Phase A and Phase A development and is currently well into Phase B. SIM-Lite the current version of SIM proposed to Astro2010, requires no new technology from the existing SIM technology.

6.1 For any technologies rated at a Technology Readiness Level (TRL) of 5 or less, please describe the rationale for the TRL rating, including the description of analysis or hardware development activities to date, and its associated technology maturation plan.

Table 3.2-1: SIM Lite Instrument MEL Part 1 with Instrument technology Readiness Levels and Basis, in section 3 provides the list of assemblies that form the SIM-Lite instrument, their TRL levels, and the rationale for the TRL assessment, such as performance testing on bread-board (bb) models or performance and environmental testing on Brass-Board (BB) models. Most assemblies are at the TRL6 or do not require new technology. A few assemblies are rated TRL5 and still need some work to reach TRL6 but this additional work is routine engineering demonstration using already well established engineering processes. These are described in the rest of this subsection.

6.1.1 Siderostat mechanism:

By the end of 2010, a Brass-Board copy of the siderostat mechanism will be built and environmentally tested. An earlier Brass-Board copy of the siderostat opto-mechanical assembly was successfully tested for thermal performance. Bread-board copies of the siderostat mechanism were successfully tested in the instrument system and sub-system demonstrations. The remaining task needed to reach TRL6 is the flight-qualification of the glass-scale encoder currently used in the mechanism. This task was estimated to cost $1M by the manufacturer and will be started has soon as funding is available.

6.1.2 Long Stroke Optical Delay Line mechanism:

A Brass-Board copy of an early version of the Long Stroke Optical Delay Line was successfully environmentally tested. It featured one-meter of travel trolley with cat'eye telescope and met the mechanical performance but not the optical performance. In the current delay line design, the cat's eye has been replaced by a corner-cube. Bread-board copies of the corner-cube based delay line were successfully tested in the instrument system and sub-system demonstrations. The remaining task needed to reach TRL6 is to build a Brass-Board or an Engineering Model of the corner-cube based Long Stroke Optical Delay Line. This task was estimated to cost $2M by the project and will be started has soon as funding is available.

6.1.3 Triple Corner-Cube optic:

A Brass-Board Double Corner Cube (DCC) was successfully build and tested. Although the Triple Corner Cube adds one more fiducial to the design, the requirements, such as surface error, are relaxed compared to the DCC. The mechanical interface, the bonding processes and fabrication techniques are all the same as the DCC. As soon as funding is available, the contract with the manufacturer will be started to build an Engineering Model of the Triple Corner Cube, which will cost about $1M.

6.1.4 Metrology Source Optical Bench:

A Brass-Board Source Optical Bench was successfully built and tested; however, we learned from that design that the integration was very labor intensive and therefore expensive. Since then, we have changed the design from a free-space to a fiber-coupled version. Although this design change requires repeating the vibration and thermal verification, to ensure that all the fiber coupling holds position, it will save money overall because the integration will be much easier. Fiber-coupled metrology sources have been used in the instrument system testbed demonstrations and have met the required performance. A single component has already been Brass-Boarded and vibration-tested to show that we have the needed technology and methods to fiber couple the components. Completing an integrated Brass-Board metrology source bench and testing will cost $3M.

6.1.5 Acousto-Opto-Modulators:

A free space version of the Acousto-Optic Modulators (AOMs) was successfully environmentally tested as 4 units that were integrated into the Metrology Source Brass-Board. Also, free-space and fiber-coupled AOMs have been used in the instrument sub-system demonstrations and have met the required performance. However, life testing of fiber-coupled AOMs still needs to be done to reach TRL6. This will cost $2M.

6.1.6 Laser Pump Diodes:

Commercial parts have already been identified to build up the laser pumps, which meet SIM Lite's life-time and power requirements. A bread-board version of the pump diode modules has been built. The packaging of the flight laser pump diodes has to be slightly changed for space environment, on which we will then perform our independent reliability and life-time test under the appropriate space-like conditions. This will be done as soon as funding is available and will cost $2M.

6.1.7 Metrology beam-launcher and postamp read electronics:

A bread-board version of the metrology electronics was built, tested in the system and sub-system demonstrations and has met the required performance. All components are flight traceable, including the field-programmable gate array (FPGA). To reach TRL6, a Bass-Board version of the design will be built and tested under the appropriate environmental conditions. his is standard electronics development.

6.1.8 Strain Gauge read electronics:

A bread-board version of the electronics has been built at JPL for a ground based project. By the end of 2009, it will be tested with the Brass-Board unit of Fine Steering Mechanism to ensure that the SIM-Lite performance requirements are met. Once funding is available, we will build a Brass-Board version to complete the design.

6.2 Describe the critical aspect of the enabling technology to mission success and the sensitivity of mission performance if the technology is not realized.

The required technology to meet the science objectives has been met under the relevant thermal and vacuum environment. The remaining technology tasks are to convert bread-board assemblies into flight designs that will survive the launch vibration and maintain performance for 5 years. Our experience to date has been that introducing the flight processes into the design has either not affected or has improved the performance of the hardware. The project doesn't consider the remaining work to reach TRL6 a risk to the final mission performance.

6.3 Provide specific cost and schedule assumptions by year for Pre-Phase A and Phase A efforts that allow the technology to be ready when required.

Not Applicable. SIM has completed the Pre-Phase A and Phase A development and is currently well into phase B. Completion of most of the remaining TRL5 to 6 efforts is already underway as part of the Engineering Risk Reduction efforts that will continue until the end of FY2010. Remaining activities will be completed prior to PDR, which could occur as early as the end of FY2011.

7 Mission Operations Development

7.1 Provide a brief description of mission operations, aimed at communicating the overall complexity of the ground operations (frequency of contacts, reorientations, complexity of mission planning, etc). Analogies with currently operating or recent missions are helpful. If the NASA DSN network will be used provide time required per week as well as the number of weeks (timeline) required for the mission.

Mission operations begins during Mission Integration & Test, when workstations and software will be provided by JPL and the Science Operations System (SOS) to facilitate a "test as you fly" approach.

With no cruise phase, In-orbit Check Out (IOC) operations will commence soon after SIM Lite is launched into an Earth-trailing solar orbit, which is the destination science orbit. IOC lasts for 30 days. After IOC, phase E will commence with a 120-day Science Verification period (SV) after which nominal science operations will begin.

The Deep Space Network (DSN) will provide 34-m support with a single antenna for downlinks using Ka-band. During IOC, continuous coverage will be provided. During nominal operations, 2 hours will be provided once a week for downlink using the spacecraft's High Gain Antenna (HGA), with additional coverage (8 hours at X band twice a week) provided for Doppler ranging. Uplink opportunities are concurrent with downlink and the Doppler ranging passes, but during nominal operations one command load will execute for 4 weeks.

The SOS will plan the science observation schedule and science data acquisition strategy in collaboration with the science instrument team and science office; the Mission Operations System (MOS), utilizing JPL Multimission tools and staff, will take these inputs and those of the spacecraft operations team and will produce command sequences for a 4-week duration. "Disruptive" targets of opportunity that would interrupt these command sequences are not currently planned to be supported.

As proposed, the SIM Lite science schedule would be pre-planned for the 5-year mission prior to launch and the only modification to the science activities would be via the insertion of "regular" targets of opportunity (RToOs) into the command sequences prior to uplink. RToOs allow for a change of targets within the predefined tile structure. It is envisioned that RToOs will be implemented using a table update strategy that will not require interrupting the ongoing sequence. However, the necessity to develop the initial 5-year schedule implies that the software and analysis tools to create and optimize that schedule will have been built and validated approximately 1-2 years before launch. Since uploads are constructed in 4-week segments, repeating that process incrementally with a modest frequency and ample lead time would imply a modest cost to maintain the software and to staff the replan activity itself. Flexibility is desirable, especially during the first two years, to accommodate improved knowledge of instrument and spacecraft performance, instrument and spacecraft anomalies, the discovery that one or more grid stars are not suitable for inclusion in the grid, as well improved knowledge of how astrophysical limitations of target stars will affect observing strategy. Responding to these developments would be a natural part of science operations.

The science scheduling will be based on the consolidation of groups of observations of spatially-adjacent targets into observation "tiles". An observation tile is characterized by a single nominal orientation of the inertially stable SIM Lite spacecraft for an approximate duration of one hour. It requires the observation of a common set of astrometric grid stars (an average of 6.5/tile), a guide star, and some number of science targets and their associated reference stars (if needed).

The SIM Lite observation schedule consists of grouping stars into observation tiles and arranging a sequence of tiles that meets the phasing constraints of the observations. Figure 7.1-1 illustrates the tile-observing concept and Figure 7.1-2 illustrates the concept of a sequence overlapping tiles. Further details of this observing scenario are described in Chapter 17 of the SIM Lite book (Davidson 2009, at http://sim.jpl.nasa.gov).

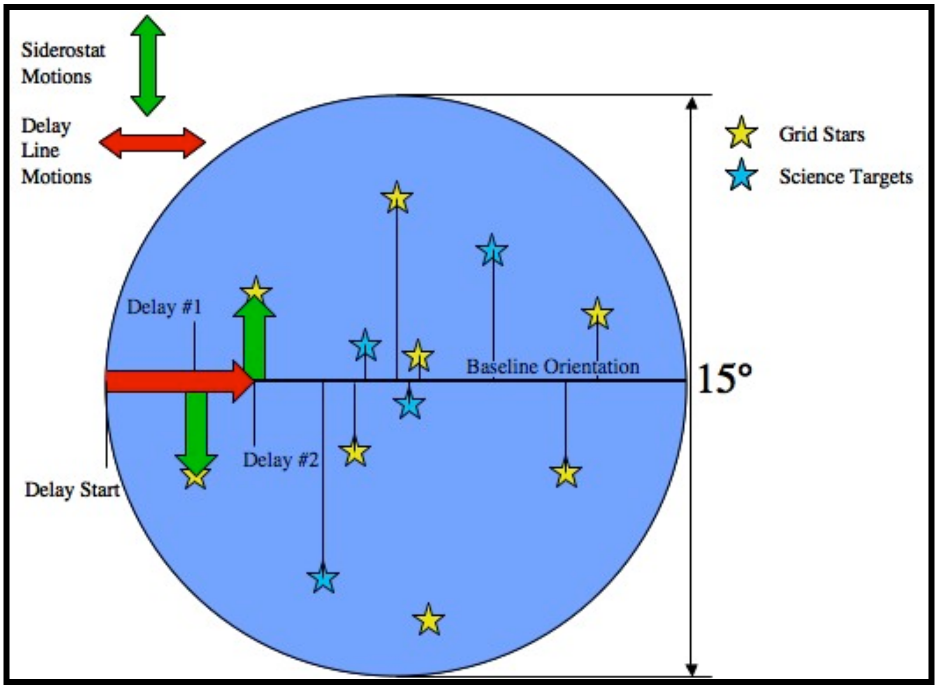


Figure 7.1-1: SIM Lite tile observing concept

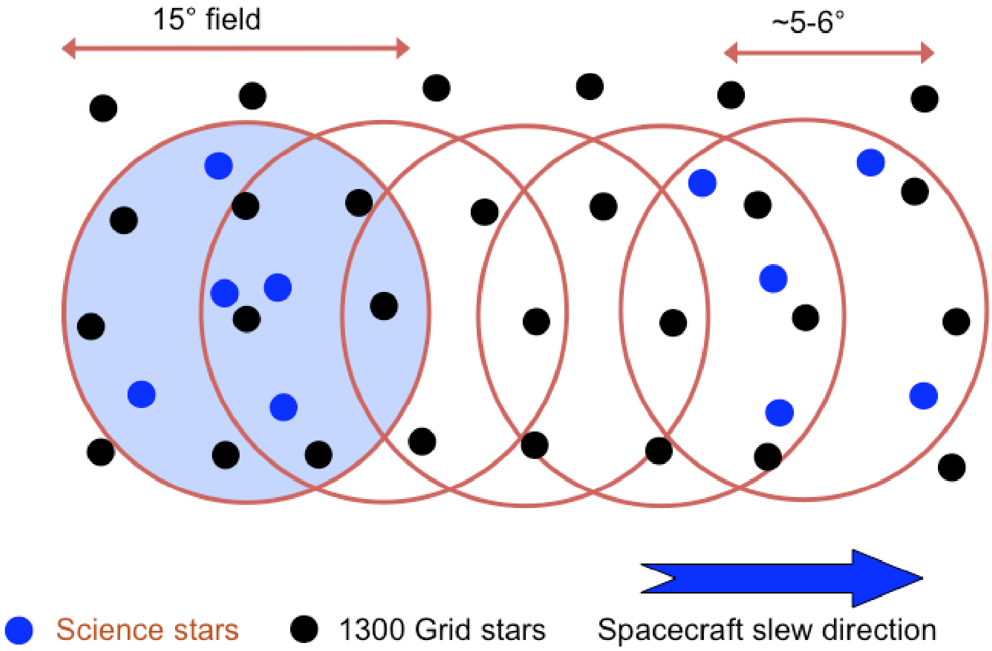


Figure 7.1-2: Sequence of overlapping tiles used to cover the entire celestial sphere.

7.2 Identify any unusual constraints or special communications, tracking, or near real-time ground support requirements.

None are identified.

7.3 Identify any unusual or especially challenging operational constraints (i.e. viewing or pointing requirements).

None of the pointing, communications or spacecraft management constraints would be considered unusual. Stray light constraints exclude measurements within an angle of 60 deg around the Sun. Other typical constraints such as minimizing large thermal transients, managing solar power inputs, managing momentum wheel velocities within a narrow range, and minimizing utilization of consumables apply to SIM Lite scheduling.

The accommodation of repeating observations of targets all over the sky with a wide range of timing requirements does represent a scheduling challenge but one which is expected to be tractable with the current generation of observation planning tools.

7.4 Describe science and data products in sufficient detail that Phase E costs can be understood compared to the level of effort described in this section.

SIM Lite will produce science data of three fundamental types: astrometric data, visibility amplitude data, and photometric data. Of these the astrometric data are the primary focus of the mission, however the other data products are necessary to both serve the interests of many science investigations with SIM and to provide critical crosschecks on the validity of the astrometric data.

All SIM Lite data products will be produced at several degrees of reduction, or levels, which are consistent across various projects at NExScI. These levels are described in Table 7.4-1.

Table 7.4-1 Science Data Product Levels

Level	Name	Description	SIM Lite Example	Team	Complexity
Level 0	Raw Data	Telemetry from spacecraft, wrappers removed, assembled into packets		GDS (JPL)	Straightforward, Standard JPL processing
Level 1 *Level 1a* *Level 1b*	Internally Calibrated Data *Decommutated* *Consolidated*	De-packetized, decommutated, time ordered data in local inertial rest frame in Engineering units, sorted into engineering, science etc. streams.	Composite delay measurement; visibility phasor	SOS	Straightforward
Level 2	Calibrated Data	Science quality data, calibrated in physical units with instrumental signatures removed, associated with relevant engineering and other ancillary data, for a given observational epoch.	Regularized delays; calibrated visibility phasors and amplitudes; non-normalized and normalized fluxes	SOS	Very complex Specialized knowledge of Interferometry and of SIM Lite Instruments required
Level 3	Consolidated Data	Science quality data, resulting from composite modeling and interpretation of one or more L-2 data items.	The SIM astrometric grid; SIM target catalog	SOS	Complex

SIM Lite will do astrometry by making interferometric *delay* measurements on astrometric targets, i.e. measuring the internal delay value where the fringes from a star are found. This delay value has dimensions of length, and is related to the baseline and star geometry and the delay bias between the starlight and internal metrology system. Higher-level astrometric results are derived from the interpretation of these delays.

SIM will also produce interferometric visibility data containing information on the morphology of SIM targets on angular scales of order 10 mas. At this spatial frequency essentially all single stars are (by design) unresolved to SIM, but there are several science use cases where the visibility amplitude (or more generally the visibility phasor) will contain important morphological information on pertinent spatial scales. Relative photometry can be deduced from the higher-level processing and calibration of the visibility data.

7.5 Describe the science and operations center for the activity: will an existing center be expected to operate this activity?; how many distinct investigations will use the facility?; will there be a guest observer program?; will investigators be funded directly by the activity?

For SIM Lite, the ground system includes a Mission Operations System/Ground Data System (MOS/GDS) at JPL based on JPL-standard multi-mission processes and a Science Operations System (SOS) based at the NASA Exoplanet Science Institute (NExScI) at the Infrared Processing and Analysis Center at Caltech. There is also a Project Science Office at JPL, which does not have day-to-day operations responsibilities.

General Observer calls are planned to make additions of (a) key project teams (joining the ten already selected by NASA (visit http://planetquest.jpl.nasa.gov/SIM/scienceMotivations/sciTeamPrograms/ for key project and mission scientist investigations already selected), (b) smaller project teams, and (c) snapshot investigators. Approximately 31% of mission time is available for General Observers (to go with 36% already assigned to the Key Projects and Mission Scientists, 2% allocated to Director's Discretionary Time, and 31% to housekeeping, including establishing the astrometric grid [pp. 175-178 in http://planetquest.jpl.nasa.gov/SIM/files/Chapter-17-LR.pdf). The SIM Lite Project will fund the investigators. These observing programs are expected to result in approximately 10,000 science stars in addition to 1300 grid stars and 3900 guide stars.

The SIM Lite SOS is housed at NExScI/IPAC. IPAC hosts the Spitzer Space Telescope Science Center (SSC) and has supported IRAS and ISO, is currently supporting Herschel and Planck, and will soon be supporting the WISE all-sky survey. NExScI operates the Keck Interferometer, oversees the selection of proposals for the NASA portion of time on the Keck Telescopes, runs the Sagan Fellowship and Summer Workshop program, houses NSTED, the NASA Star and Exoplanet Database as well as KOA, the Keck Interferometer archive, and serves as the US portal to the CNES CoRoT transit mission.

7.6 Will the activity need and support a data archive?

Yes. The archive will be developed at the NExScI Science Operations System (SOS) in collaboration with the Infrared Science Archive (IRSA) also located at IPAC. IRSA is chartered to serve calibrated science products from NASA's infrared and submillimeter missions, including the 2MASS, IRAS and MSX surveys, and the Spitzer ISO and SWAS observatory missions.

7.7 Please fill in the Missions Operations and Ground Data Systems Table

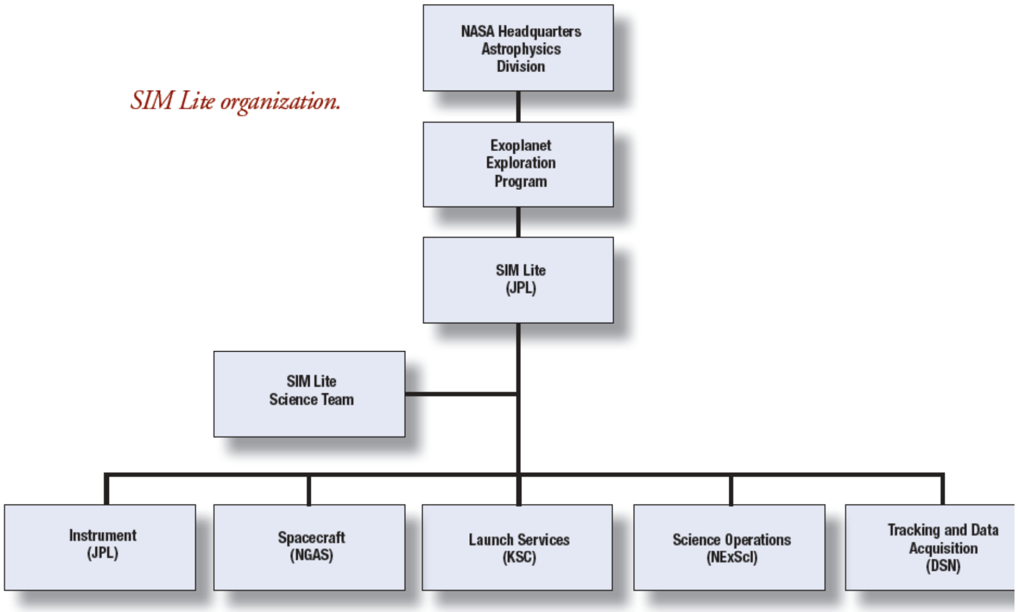
See Table 7.7-1.

Table 7.7-1: Mission Operations and Ground Data Systems Table

Down link Information	**Value, units**
Number of Contacts per Day	One 8-hour HGA Ka-band pass per week for command and telemetry. Second 8-hour LGA X-band pass per week for Doppler ranging.
Downlink Frequency Band, GHz	X-Band (telemetry & science data) Ka band (science date)
Telemetry Data Rate(s), bps	10 bps to 3.48 Mbps (X band) 10 bps to 6.4Mbps (Ka band)
S/C Transmitting Antenna Type(s) and Gain(s), DBi	2 omni-directional LGA (X band) 1.5m HGA (Ka & X-band)
Spacecraft transmitter peak power, watts.	35 W RF (Ka band) 100 W RF (X band)
Downlink Receiving Antenna Gain, DBi	DSN 34m BWG antenna @ 20 kW Xmit Power
Transmitting Power Amplifier Output, watts	35 W RF (Ka band) 100 W RF (X band)
Uplink Information	**Value, units**
Number of Uplinks per Day	Uplink concurrent with Ka-band passes (1 per week)
Uplink Frequency Band, GHz	X band
Telecommand Data Rate, bps	7.8125 bps to 4 kbps
S/C Receiving Antenna Type(s) and Gain(s), dBmi	LGA (X band): 44.5 dBmi 1.5 m HGA (Ka band): 72 dBmi

8 SIM Lite Programmatics & Schedule

8.1 Provide an organization chart showing how key members and organizations will work together to implement the Program.



SIM Lite organization.

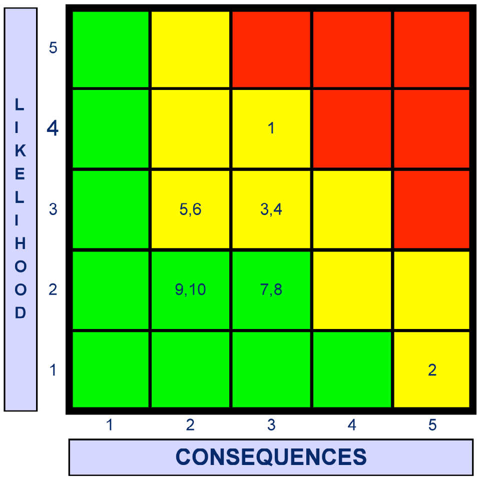
The SIM Lite organization (Figure above) brings to bear the strengths of a competitively selected science team to define the science investigations and the technical performance drivers, the Jet Propulsion Laboratory (JPL) to manage the project, develop and validate the technology, design and build the 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 1, 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.

8.2 Provide a table and a 5 by 5 risk chart of the top 8 risks to the program. Briefly describe how each of these risks will be mitigated and the impact if they are not. (Mass, power, schedule, money, science, etc.).

Risk Descriptions:



LIKELIHOOD					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨 1	🟥	🟥
3	🟩	🟨 5,6	🟨 3,4	🟨	🟥
2	🟩	🟩 9,10	🟩 7,8	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨 2
	1	2	3	4	5
	CONSEQUENCES				

Criticality	LxC Trend**	Approach
🟥 High	⇩ Decreasing (Improving)	M - Mitigate
🟨 Med	⇧ Increasing (Worsening)	W - Watch
🟩 Low	⇨ Unchanged	A - Accept
	☐ New since last Month	R -Research

Rank & Trend		Risk ID	Appro ach	Risk Title
1	⇧	SIM-19	A	Loss of key personnel due to funding/schedule delays/changes
2	⇨	SIM-24	A	Launch Vehicle failure during launch or orbit insertion.
3	⇨	SIM-1	W	Potential ELV cost increase
4	⇨	SIM-29	R	Insufficient S/C avionics spares
5	⇨	SIM-16	R	Resource Impact of potential SIM Redundancy/Rel architecture
6	⇨	SIM-21	W	Spacecraft Development Lag (relative to the instrument)
7	⇨	SIM-27	R	Payload system I&T
8	⇩	SIM-28	R	Instrument CCD-cooling Heat Pipe Heritage
9	⇩	SIM-25	R	Spacecraft Bus density and growth capability
10	⇨	SIM-26	A	PSS Joint Stability

8.2.1 Loss of key personnel due to funding/schedule delays/changes.

a) Risk description: Delay in full-scale development results in loss of key personnel who developed the instrument technology (completed in 2005).

b) Mitigation approach: Current Engineering Risk Reduction brassboard hardware development is retaining some of these key people through the end of FY 2010. The funding profile in Table 9.4-1 would fully mitigate this risk.

c) Impact of mitigation failure: Impact depends upon the magnitude of the delay in full-scale development. Loss of all key personnel due to a significant delay will have a substantial (but TBD) impact on cost and schedule due to new personnel needing to relearn (from project records) what has been learned from the technology program. More mistakes will likely be made in building the flight hardware. A full EM program could be added to the instrument development program to mitigate this somewhat, but at substantial additional cost.

8.2.2 Launch vehicle failure during launch & orbit insertion.

a) Risk description: Launch vehicle fails to deliver SIM Lite to the proper orbit.

b) Mitigation approach: Use only launch vehicles that meet NASA reliability criteria and use experienced KSC launch services to ensure the launch vehicle is properly processed.

c) Impact of mitigation failure: Loss of mission.

8.2.3 Potential ELV cost increases.

a) Risk description: ELV costs have fluctuated significantly over the past decade and are likely to continue to do so. For example, KSC provided a range in cost from $210M FY09$ to $270M FY09$ for an intermediated class launch vehicle for a 2015 launch readiness date. The project used the average

($240M FY09$) in its estimate but could need an additional $30M to achieve the $270M number if it comes to that. NASA SMD requires that increases be funded from project reserves.

b) Mitigation approach: There is little that the project can do to mitigate this, since it is based upon LV costs negotiated by KSC.

c) Impact of mitigation failure: N/A.

8.2.4 Insufficient spacecraft (S/C) avionics spares.

a) Risk description: During the SIM Lite 2008/2009 Aerospace ICE, Aerospace expressed concern that, while NGAS was planning to have S/C EM hardware, flight spares were not provided, which could lead to schedule/cost growth should failures occur during Mission I&T.

b) Mitigation approach: Several mitigation approaches will be used: 1) Flight components will be procured so that rapid repairs can be made to any flight avionics boards that fail during Mission I&T; 2) EM hardware will be form-fit-function to the flight hardware so that, for non-environmental testing, the EM hardware can substitute while repairs are being made to the flight hardware; 3) Single string S/C operations are possible during environmental testing if required to hold schedule while flight hardware repairs are being made; and 4) Funded schedule reserve is provided to accommodate delays from all causes, including such avionics hardware repairs.

c) Impact of mitigation failure: Impact depends upon the magnitude and extent of the S/C avionics hardware failures and can range from none to months, some of which can be accommodated by funded schedule reserve and schedule workarounds as discussed above.

8.2.5 Resource impact of potential SIM instrument redundancy/reliability architecture.

a) Risk description: While the spacecraft is fully redundant, because of its nature, the instrument is not. Though the instrument redundancy is consistent with the project single point failure exception policy and has been reviewed by external teams, the potential exists for external reviewers at some point to recommend/mandate additional redundancy that could increase instrument complexity and cost.

b) Mitigation approach: The project plans to obtain formal JPL and NASA senior management approval for the SIM Lite instrument redundancy approach within the coming year (2010).

c) Impact of mitigation failure: Additional (TBD) hardware and cost may be required.

8.2.6 Spacecraft development lag.

a) Risk description: With recent funding reduction, engineering risk reduction efforts have been rightly focused on the instrument, where the majority of the development risk resides. If the project goes forward in fiscal year 2011, it is unlikely that NASA SMD will have funds to optimally fund the full scale development of the whole project for a 2015 launch, which will likely result in a slow ramp up in funding over several years, in which case the project would develop the instrument first in order to retire risk and delay the development of the remainder of the mission systems. This could result in a situation in which the S/C might incur additional costs due to accommodating the resulting instrument.

b) Mitigation approach: Should the project go forward with limited funding ramp up, a detailed Interface Control Document (ICD) will be developed and maintained for the spacecraft and a minimal S/C team will be retained to support the S/C side of that ICD, with the intent that accommodation issues will be resolved early.

c) Impact of mitigation failure: Some additional accommodation cost may be incurred.

8.2.7 Payload System I&T:

a) Risk description: Due to the instrument configuration, complete test-as-you-fly is not possible. A test + model based V&V approach was developed and demonstrated in Technology Gate #8 and heavily reviewed as providing appropriate V&V of system performance. Based upon the technology development experience, where an enormous amount of time was spent chasing ground support equipment (GSE) induced anomalies during the MAM testbed field-dependent picometer (knowledge) testing, the project has chosen to accept the risk of not performing the field-dependent picometer (knowledge) test pre-launch.

b) Mitigation approach: Field-dependent nanometer (control) and field-independent picometer (knowledge) testing are performed during instrument I&T. This approach is based upon knowledge gained from the ten-year SIM technology development program where the field-dependent test did not discover problems with the test unit but required a large expenditure of effort to isolate GSE induced issues. The project believes that the risk from this approach is acceptable and avoids large cost/schedule uncertainty during instrument I&T.

c) Impact of mitigation failure: If there was a field-dependent picometer (knowledge) issue that was not uncovered until after launch, there may be on-orbit performance degredation. This is considered unlikely, though, since the on-orbit environment, based on both modeling and the flight experience of other missions, is expected to much more benign than the laboratory environment, likely resulting in overall system performance significantly better than can be measured in the laboratory, which may compensate for any missed field-dependent picometer (knowledge) performance.

8.2.8 Instrument detector cooling heat pipe heritage:

a) This is a risk that was identified during the Aerospace ICE in late CY2008. The concern was that the loop heat pipes proposed for cooling the Astrometric Beam Combiner (ABC) CCDs had not been previously flown, raising some concern about whether they would perform adequately in zero G.

b) Mitigation approach: As a result of the Aerospace concern, the project has completed a CCD-cooling trade study that has resulted in a change to a Diode Heat Pipe with flight heritage.

c) Impact of mitigation failure: None expected.

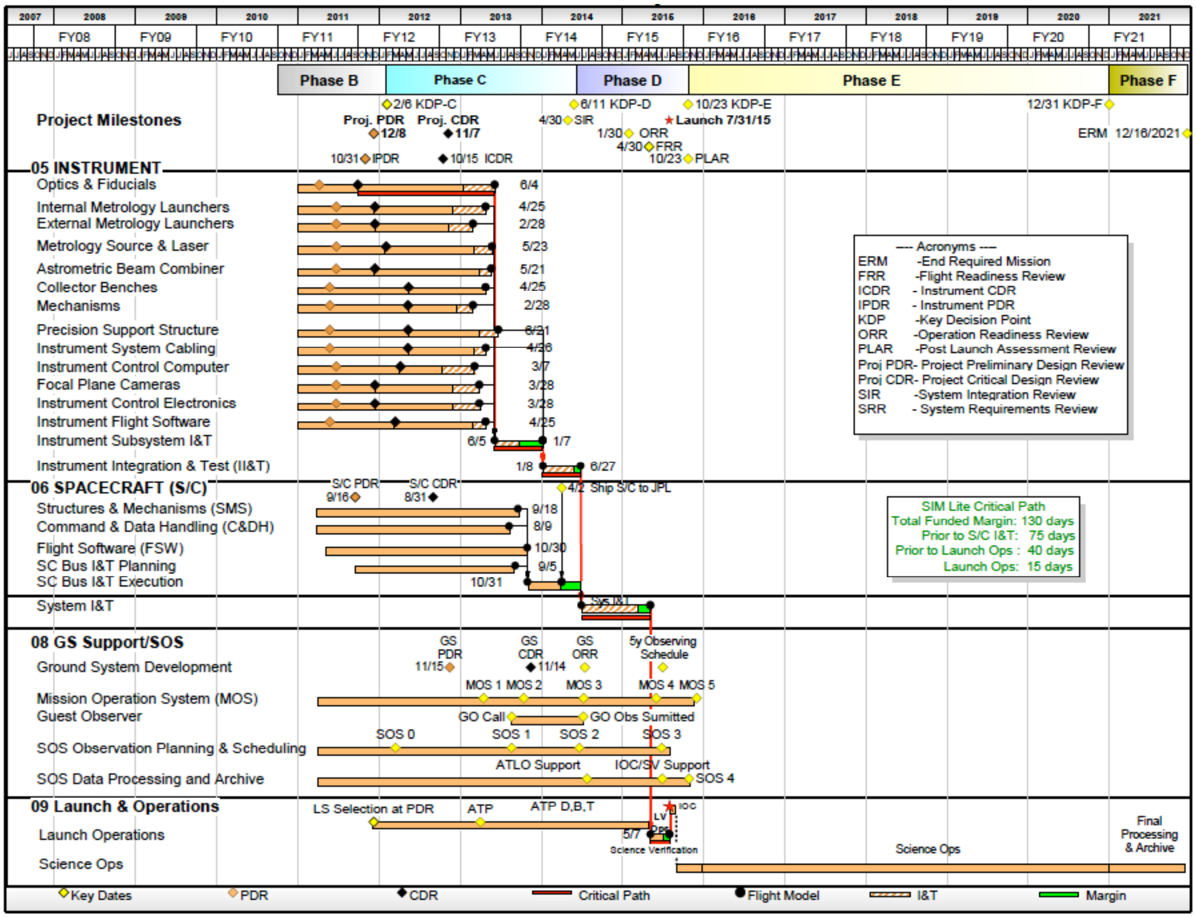
8.3 Provide an overall (Phase A through Phase F) schedule highlighting key design reviews, the critical path and the development time for delivery required for each instrument, the spacecraft, development of ground and mission/science operations, etc.

The SIM project entered Phase A in October 1997 and entered Phase B in August 2003, where it remains. Multiple programmatic changes have taken place over these years, partly due to launch vehicle changes (ELV to Shuttle to EELV) and partly due to direction from NASA HQ to redesign to lower cost targets (multiple times). The SIM Lite Astrometric Observatory was the latest redesign that was undertaken by the project itself in an attempt to explore the lowest cost options using the completed SIM technology.

The SIM Lite schedule shown below (and shown in the schedule tables later in this section) is the schedule used during the SIM Lite Independent Cost Estimate conducted by the Aerospace Corporation from October 2008 through January 2009 under contract to NASA HQ.

The Aerospace Corporation expressed concern that, while the Phase A and B durations for SIM were much longer than typical for comparable missions, the durations of the remaining phases were somewhat shorter than average and expressed that their estimate of a 70% confidence schedule would be about 9 to 11 months longer than the project's schedule provided.

An alternate schedule (not shown here) was provided to NASA's SMD APD director, Jon Morse, in May 2009 in response to a request to provide a cost/schedule that fit within one half of the total of the NASA APD Future Mission lines in the 2010 NASA budget. This scheduled delayed all development activities except for the Instrument and resulted in a January 2018 launch readiness date (one and a half years later than the schedule shown below). While this alternate schedule appears credible, it does not have the same level of detail behind it that the July 2010 launch readiness date schedule has.



8.4 Fill out the Key Phase Duration table, indicating the length of time required (months) for: each Phase (A through F), ATP to PDR, ATP to CDR, and other key metrics for schedule analysis (ATP to instrument delivery, spacecraft delivery, observatory delivery and launch).

See attached table 8.4-1.

Note that dates given in the attached tables are the actual SIM Phase A and B start dates. Although a large part of the concept and preliminary design activities for SIM are directly applicable to SIM Lite, the durations of Phase A and B are probably not directly comparable to pre-Phase A missions currently estimating such durations. During the NASA HQ directed Aerospace Corporation SIM Lite Independent Technical/Cost/Schedule Estimate (Oct 2008 through Jan 2009), rough estimates for “equivalent Phase B” start dates were worked out (Optimistic, Estimated, Pessimistic) as part of the schedule risk assessment. While these have not been reproduced here, Aerospace Corp still has these materials and those estimates.

8.5 Fill out the Key Event Dates table, indicating the dates (month/year) for the key development and operations milestones.

See attached table 8.5-1.

Note that, as for the previous table, the end of Extended mission has been changed to “End of Mission – Data Archive & Project Closeout”, which correctly represents the end of the actual end of the required mission. An extended mission is not currently planned for SIM Lite.

Table 8.4-1: SIM Lite Key Phase Duration Table

Project Phase	**Duration (Months)**
Phase A – Conceptual Design*	69
Phase B – Preliminary Design*	102
Phase C – Detailed Design	28.5
Phase D – Integration & Test	14.5
Phase E – Primary Mission Operations	64
Phase F – Data Archive and Project Closeout**	12
Start of Phase B to PDR*	98
Start of Phase B to CDR*	110
Start of Phase B to Delivery of Instrument #1*	130
Start of Phase B to Delivery of Instrument #2*	N/A
Start of Phase B to Delivery of Instrument #n*	N/A
Start of Phase B to Delivery of Spacecraft*	131
Start of Phase B to Delivery of Observatory*	141
System Level Integration & Test	10.3
Project Total Funded Schedule Reserve	10.5
Total Development Time Phase B – D*	145

*** Based upon *Actual* SIM PhA & B start dates. During the SIM Lite Aerospace ICE, an "estimated equivalent PhB" start dates for SIM Lite were estimated (optimistic, rough estimate, and pessimistic) for use in schedule risk analysis. These have not been used here.**

**** NASA Phase F is the project closeout phase that occurs after on-orbit operations are complete. For SIM Lite, there is no extended mission planned but 12 months of final data processing, data archival and project closeout are planned. This is Phase F for SIM Lite.**

Table 8.5-1: SIM Lite Key Event Dates

Project Phase	**Milestone Date**
Start of Phase A	10/30/1997
Start of Phase B	8/1/2003
Preliminary Design Review (PDR)	10/1/2011
Critical Design Review (CDR)	10/1/2012
Delivery of Instrument #1 (DoI-1)	6/1/2014
Delivery of Instrument #2 (DoI-2)	N/A
Delivery of Instrument #n (DoI-n)	N/A
System Integration Review (SIR)	5/1/2014
Pre-Ship Review (PSR)	5/1/2015
Launch Readiness Date (LRD)	7/1/2015
End of Mission – Primary (EoM-P)	12/1/2021
End of Mission – Data Archive & Project Closeout	12/1/2022

Tables. No page count.

9 Cost

The answers to the questions in this section should be relatively self-contained. Additional information regarding the SIM Lite cost estimates can be found in the SIM Lite Project's response Astro2010 RFI Part 1, available at http://sim.jpl.nasa.gov under */Astro2010 Decadal Survey*.

Note that the SIM Lite costs summarized in tables 9.1-1 and 9.4-1 are based upon the JPL Internal Grass Roots estimate. Also note that the cost estimates summarized in this document do not constitute an implementation-cost commitment on the part of JPL or Caltech.

9.1 *Provide manpower estimates and cost by year/Phase for all expected scientists that will be involved in the mission.*

The following table provides an estimate of the SIM Lite funding going to scientists involved in the mission. These include: (1) Project science office personnel, (2) Existing AO-1 Science Teams, (3) General Observer program personnel, and (4) Science Operations System (SOS) personnel. While this table also shows historical funding to scientists supporting the project through 2010, for the purposes of this Decadal Survey, costs prior to 2011 should be considered sunk (historical) costs, already spent. Note that an astrometry mission requires considerable preparatory science, which has been funded since the first competitive science team selection (AO-1) in 2000.

Table 9.1-1: Funding for SIM Lite scientists (science office, teams and operations); RY$K.

Real Year $	Prior	2010	2011	2012	2013	2014	2015	Phase E/F	Total RY09$	Total FY09$
Sunk Cost (PhA & B thru FY10):										
Cost	$ 51,944	$ 4,268							n/a	n/a
Workyears	260	21								
Phase B (Cost-to-go):										
Cost			$ 12,200	$ 5,044					$ 17,244	$ 16,237
Workyears			98	40					138	
Phase C/D										
Cost				$ 10,282	$ 20,776	$ 24,108	$ 24,709		$ 79,876	$ 70,362
Workyears				83	166	193	198		640	
Phase E										
Cost								$ 135,960	$ 135,960	$ 106,771
Workyears								1088	1,088	

9.2 *If ESA or another key partner is assumed to be a partner or major contributor, provide an estimate by year and Phase for the breakdown between NASA and ESA (or other) contributions. This should be separate, but consistent with Total Mission Cost Funding Table.*

Not applicable for SIM Lite.

9.3 *Provide a description and cost of what will be performed during Phase A by year. Also include total length of Phase A in months and total Phase estimated costs.*

SIM entered Phase A in October 1997 and completed Phase A in August 2003, for a total of 69 months in Phase A. Total Phase A funding was $206M RY$. During Phase A, the following activities were accomplished:

a) Significant progress towards completion of SIM focused technology development (technology development completed in July 2005 during Phase B).

b) Major Industry Partners competitively selected in October 1998 (Lockheed Martin Sunnyvale for the instrument and TRW, now NGAS, for the Spacecraft, PSS and Mission I&T). Lockheed dropped in October 2003 for several reasons.

c) SIM Science Team competitively selected in November 2000 through NASA HQ Announcement of Opportunity. Ten Key Projects and five Mission Scientists selected, with their teams comprising roughly 70 scientists.

d) SIM conceptual re-design completed for a Delta III expendable launch vehicle for insertion into an Earth-trailing Solar orbit (pre-Phase A concept was for a low Earth orbiter that proved not feasible due to thermal instability induced by Earth shine).
e) SIM conceptual redesign completed for an STS (shuttle) launch at direction of NASA HQ . STS Columbia was the target launch vehicle (Columbia was lost February 1, 2003, initiating a major redesign for an EELV that was completed in July 2005 during Phase B).
f) Supported CAA review of SIM in May 2002.
g) Held SIM Preliminary Mission and System Review in April 2001 (KDP-B transition review).

9.4 Please fill out the Mission Cost Funding Profile table assuming that the mission is totally funded by NASA and all significant work is performed in the US.

Please see Table 9.4-1: SIM Lite Mission Cost Funding Profile table, attached.

This table contains actual sunk costs through government Fiscal-Year (FY) 2009, totaling $590M Real Year dollars, and the estimated cost for FY2010 based upon NASA funding commitments for FY2010 (which might be subject to change). Together, these total some $609M Real-Year dollars. This sunk cost represents the completion of the SIM technology program; multiple mission redesigns to accommodate launch vehicle changes, NASA HQ directed cost reduction studies; science team selection and funding of preparatory science; a substantially completed payload and spacecraft preliminary design; brassboard development and flight qualification testing of most payload assemblies; and much more.

Costs from FY2011 through end of mission are those of the Project's internal estimate of the life cycle cost to go.

During the Aerospace Independent Technical/Cost/Schedule estimate, a method was worked out to identify the "equivalent Phase B" part of these sunk costs so that Aerospace models that compute costs for Phase B/C/D together could have this equivalent Phase B cost subtracted such that an estimate of the life cycle cost to go could be obtained from their models. Aerospace actually developed three Phase B sunk cost estimates (optimistic, estimated, and pessimistic) that were all three used in the Aerospace schedule risk analysis. No attempt has been made to reconstruct those estimates here.

Section 2 of this document, "Programmatic,Cost & Science History", contains a table of successive cost estimates (reproduced below as Table 9.4-2, for convenience), including sunk cost (in real-year dollars) at the time of the estimate and lifecycle-cost-to-go (in government fiscal year 2009$). The last column in this table shows three SIM Lite cost estimates: (1) JPL's Team X, shown for comparison with

Table 9.4-2: SIM Estimate history since the 2002 CAA review, $M.

$M	Redesign2001	ICR 2003	Redesign2005	**SIMLite2008***
Launch Vehicle:	(STS)	(STS)	(EELV)	**(EELV)**
Sunk cost (**Real Year $**)	$ 130	$ 200	$ 380	**$ 590**
LCC-to-go (**Fiscal Year 2009$**)				
- JPL Team X:	N/A	N/A	N/A	**$ 1,110**
PhBCD, w/reserves, w/o LV				**$ 790**
Launch Services (LV) (AV521)				**$ 170**
Operations (Phase E)**				**$ 150**
- JPL Project Grass Roots	$ 1,530	$ 1,930	$ 2,210	**$ 1,410**
PhBCD, w/reserves, w/o LV	$ 1,080	$ 1,310	$ 1,520	**$ 1,010**
Launch Services (LV)	$ 140	$ 190	$ 260	**$ 240**
Operations (Phase E)**	$ 310	$ 430	$ 430	**$ 160**
- Independent Cost Estimate	$ 1,570	$ 1,890	$ 2,100	**$ 1,650**
PhBCD, w/reserves, w/o LV	$ 1,130	$ 1,250	$ 1,410	**$ 1,260**
Launch Services (LV)	$ 140	$ 220	$ 260	**$ 240**
Operations (Phase E)** †	$ 300	$ 420	*$ 430*	**$ 150**
* Assumes an FY2011 resumption of development.				
** Five year required mission only.				
† PhE ICE not done for 2005 Redesign. Used project PhE estimate (italics).				

other missions that obtained a JPL Team X or GSFC equivalent estimate; (2) the JPL Project estimate; (3) the January 2009 Aerospace independent cost estimate. Further details for all of these estimates can be provided upon request.

9.5 For those partnering with ESA, JAXA, or other organizations, provide a second Mission Cost Funding Profile table and indicate the total mission costs clearly indicating the assumed NASA and contributed costs.

Not applicable to SIM Lite.

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.

Table 9.4-1: SIM Lite mission cost funding profile (including sunk costs); k RY$

TOTAL MISSION COST FUNDING PROFILE – US Only

(FY costs[1] in Real Year Dollars, Totals in Real Year and 2009 Dollars)

Item	Prior	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	Phase E/F	Total (Real Yr.)	Total (FY 2009)
Cost										
Phase A Concept Study	$202,421	$0	$0	$0	$0	$0	$0	$0	$202,421	$253,830
PM/SE/MA	$36,899	$2,475	$14,105	$21,243	$19,717	$18,194	$13,762	$0	$126,395	$120,904
Instrument PM/SE	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Instrument A	$227,425	$11,250	$80,922	$127,692	$92,499	$35,372	$20,444	$0	$595,604	$585,837
Instrument B	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Spacecraft including MSI&T [2]	$65,156	$578	$65,560	$76,228	$52,020	$11,063	$17,542	$0	$288,147	$275,941
Pre-launch Science	$34,693	$4,268	$7,854	$9,187	$8,900	$8,824	$8,471	$0	$82,197	$79,801
Ground Data System Dev (SOS)	$15,374	$0	$6,419	$9,912	$20,269	$27,405	$31,456	$0	$110,835	$101,805
Total Dev. w/o Reserves	$581,968	$18,571	$174,860	$244,262	$193,405	$100,858	$91,675	$0	$1,405,599	$1,418,119
Development Reserves	$982	$339	$26,264	$36,676	$106,547	$60,719	$55,166	$0	$286,693	$256,011
Total A-D Development Cost	$582,950	$18,910	$201,124	$280,938	$299,952	$161,577	$146,841	$0	$1,692,292	$1,674,130
Launch services	$167	$0	$341	$992	$97,862	$97,887	$80,509	$0	$277,757	$243,687
MO&DA [3]	$0	$0	$0	$0	$0	$0	$0	$179,130	$179,130	$140,673
MO&DA Reserves	$0	$0	$0	$0	$0	$0	$0	$26,870	$26,870	$21,101
Education/Outreach	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Other; ONC	$5,358	$90	$3,020	$4,218	$4,504	$2,429	$2,207	$3,090	$24,916	$23,244
Total Cost	$588,475	$19,000	$204,485	$286,148	$402,318	$261,893	$229,557	$209,090	$2,200,965	$2,102,836
						Total Mission Cost				**$2,102,836**

1 Costs should include all costs including any fee

2 MSI&T - Mission System Integration and Test and preparation for operations

3 MO&DA - Mission Operations and Data Analysis

Table. No page count.