SIM Science Operations

S. C. Unwin

Jet Propulsion Laboratory, California Institute of Technology,
Mail Stop 301-486, 4800 Oak Grove Drive, Pasadena, CA 91109, U.S.A.

ABSTRACT

This paper describes the science scheduling and operation of the Space Interferometry Mission (SIM) as a science instrument. The SIM Science Team has defined a set of science programs to be observed with SIM. The scheduling and operation of SIM, and modeling of the expected performance, differs significantly from other astrometric or imaging space-based telescopes. A timeline of observations is developed using a scheduling unit called a 'tile' - a set of related science and reference star observations made while the instrument is inertially pointed. Global astrometry, for measuring stellar distances and velocities, is performed by observing multiple overlapping tiles covering the whole sky. Most observing program require many short observations over the life of the mission, which poses interesting challenges for scheduling tools in developing the science timeline. Development of these tools will be done by the Interferometry Science Center at Caltech. Planning tools will allow users to perform trades of the expected science performance, for instance, by varying the number of observations of a target against the time spent on an individual observation. The search for planets will require careful optimization of the selection of target and reference stars in a tile, and their observing sequence, to minimize instrumental systematic errors which may be a function of direction on the sky or due to thermally-induced drifts in the instrument.

Keywords: Space Interferometry Mission, SIM, Operations, Astrometry, Planet Detection, Stellar Astrophysics

1. INTRODUCTION

The Space Interferometry Mission (SIM) will be the first astrometric instrument capable of measurement to a precision of a few microarcseconds. SIM is a Michelson interferometer with a 10-m baseline, operating in the optical waveband. It will be placed in a drift-away solar orbit, following launch in 2009. It is designed to reach an accuracy of 4 μas for global astrometry, on objects as faint as magnitude $R = 20$, and 1 μas in a single measurement relative to local reference frame, as will be used for planet searches. This performance is a factor of at least 100 improvement over the current state of the art, and it open up a wide range of exciting problems in astronomy which can be tackled with this kind of capability. In 2000, NASA selected the SIM Science Team comprising 15 scientists from a broad range of astronomy disciplines, to help JPL develop the science requirements which define the mission, and to develop their own programs of observations to be conducted by SIM. The approved Science Team programs will be used as the basis for requirements on the instrument performance, and for developing an observing plan which delivers science data from the instrument to each scientist. An overview of the SIM science program is given by Shao[1] (see also Ref. 2).

This paper discusses how SIM is operated as a scientific instrument. Analogies with ground-based optical interferometers, or from other astrometric space missions are of limited utility, because of a number of major differences in the way the interferometer must be operated. We first summarize the basic operation of SIM as a flight instrument (see Ref. 3 for more detail), then describe how science measurements are made from individual instrument measurements. There are many requirements on both the instrument, and on reference stars across the sky, for a successful mission. We describe how each of these contraints influences both the way the science mission is planned, and how the detailed observing timeline for each type of measurement is constructed.

Further author information: E-mail: stephen.unwin@jpl.nasa.gov

2. SIM SCIENCE PROGRAM

SIM will make contributions to a very wide range of problems in astrophysics. Most notably, it will search for low-mass planets areound nearby stars, using the well-known astrometric 'wobble' signature of the parent star. SIM will make at least two unique contributions to the rapidly-growing field of extrasolar planets: (1) it will be the first instrument to definitively answer whether planets with masses as small as the Earth's exist around stars in our solar neighborhhood; (2) it will measure the mass of every planet it detects. Mass is one of the most fundamental quantities in astrophysics; in the case of planets it is important for understanding whether the planet can retain an atmosphere, and for learning about how the planet formed and its eventual fate in what is typically a semi-chaotic dynamical environment. Three of SIM's 10 Key Projects are devoted to the study of nearby planetary systems.

Other Key Projects address a range of problems in stellar, Galactic and extragalactic astrophysics. Astrometry of 'exotic' objects, including black holes, and neutron star binaries, allows accurate masses for these objects to be measured for the first time. Precision measurements of stellar masses are notoriously difficult, and both extreme ends of the stellar main sequence are poorly known at present. These are straightforward, but absolutely fundamental, measurements for SIM to make. In Galactic structure, SIM will measure both distances (via parallax) and proper motions to samples of dynamicaly interesting stars. Of particular interest are the stellar remnants of the formation of our Galaxy, including encounters with smaller galaxies which have largely merged with the Galactic bulge or halo. Accurate proper motions, along with ground-based radial velocities allow the 3-D motions to be reconstructed; these will be used to trace the gravitational potential of the Galaxy and the history of mergers.

These exciting programs being planned for SIM by the Science Team give an idea of the science opportunities that SIM represents. Currently, less than half of the total available observing time has been assigned to the Science Team. A fraction of the remaining time will be awared competitively via a second NASA Announcement of Opportunity (AO) to be issued well before SIM launch. There will also be a modest Guest Observer (GO) program, with some proposals selected shortly before launch, and some during the mission. Managing these programs is a challenge, because SIM science data are synoptic in nature (see Section 7): virtually all of the science is in the variation of the position of the targets, whether they be due to parallax or proper motion. Most will require data aquired over the 5 years of SIM's life. Thus, most of SIM's observations will be pre-planned before launch, which is why the first and second AOs come early, to allow time for selection and characterization of the targets. However, since SIM is a pointed instrument (not a survey), it can observe targets at short notice. Some observing time will be held back for 'targets of opportunity' and some small astrometry programs proposed early in the mission timeline.

SIM will spend a fraction of its science observing on a 'grid' of ~ 1300 stars over the whole sky which will define the reference frame for SIM's global astrometry. These data support a range of SIM programs, and will be the responsibility of the SIM Project to schedule, observe, and analyse. A scientific analysis of the grid observations will be performed, but the details have yet to be defined. For instance, the grid data provide, in principle, an accurate measure of the general relativistic PPN γ parameter to a level of about one part in 10^5.

3. SCIENCE MEASUREMENTS

3.1. Targeted astrometric measurements

SIM differs fundamentally from other space based astrometric instruments such as Hipparcos,[4] FAME,[5] and GAIA[6] - all of which are scanning instruments - in that it conducts pointed observations, not a survey. Scanning instruments lend themselves to operating in a pre-planned survey mode, covering targets to some limiting magnitude over the whole sky. Since the observing pattern is fixed by the instrument and mission design, the per-target integration time is also fixed (though it may vary with position on the celestial sphere), and hence the astrometric accuracy is a function of target magnitude. With a pointed astrometric instrument like SIM, or ground-based astrometric interferometers like PTI,[7] NPOI[8] and the Fine Guidance Sensors on the Hubble Space telescope (FGS/HST[9]), target lists are prepared in advance, and the astrometric accuracy is a function of the observing time invested in each target. Pointed instruments like HST and SIM are intrinsically less efficient

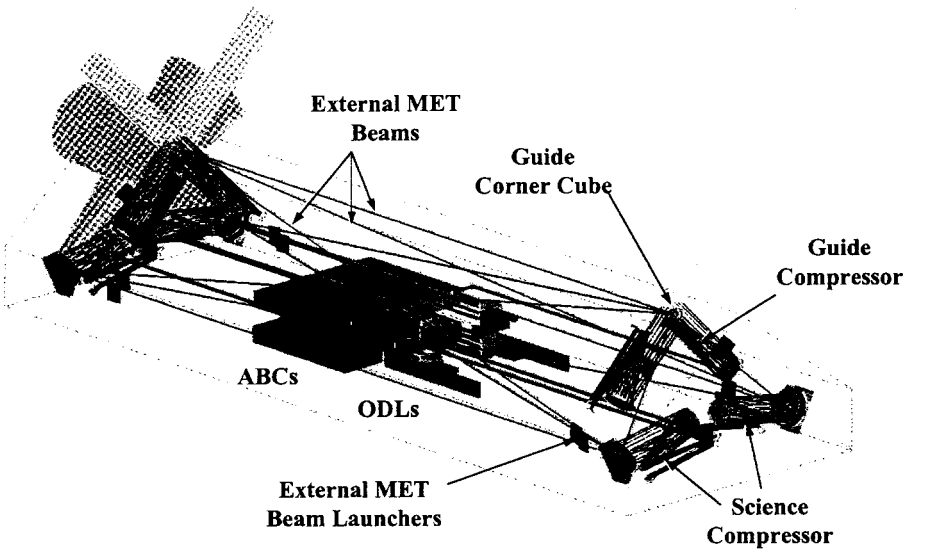

Figure 1. Schematic representation of the SIM flight system, showing the acceptance angles of the guide interferometers (narrow cones), and the science instruments (wide cone).

than survey instruments, which may have a duty cycle approaching 100%, but they have the big advantage that observing programs can be tailored to meet the sceince goals for each target individually, and in particular the measurement acuracy can approach the fundamental instrument limit even for very faint and distant targets.

There is a single science instrument on SIM, operated in three different modes for various science objectives: (1) wide-angle (global all-sky) astrometry, for which the basic stellar parameters are mid-epoch position, parallax, and proper motion; (2) narrow-angle astrometry, for which relative measurments of the same quantities, but to higher precision, are made over a narrow field of view; and (3) synthesis imaging demonstration, in which the instrument sequentially samples the aperture (u, v) plane for a resolved target. This latter mode is intended primarily as a flight demonstration of synthesis imaging in space, for much larger future instruments. There is, of course, 40 years of experience with similar measurements on the ground.[10] Figure 1 shows the overall design of the flight system; only one science instrument is operated at any one time, but in the event of a failure, the second science instrument can operate as either a science or a guide interferometer.

Detailed simulations of the instrument performance are underway[11]; this effort, called SIMsim, models the instrument operation from photon detection and readout from the CCD (millisecond timescales) through to the entire mission (5 years). As the flight instrument becomes better defined, the design parameters will be used to enhance the fidelity of the SIMsim model.

3.2. Instrument field of regard

SIM is designed to observe targets with a field of regard of diameter 15°, without moving the spacecraft orientation. It achieves this through the use of a pair of guide interferometers, which observe bright stars continuously throughout a sequence of measurements of science targets with the third interferometer. The guides perform three tasks: (1) they sense attitude motions of the nominal boresight direction at the microarcsecond level, orders of magnitude below that sensed by the attitude control system, and feed forward corrections to the position of the white-light science fringes; (2) they sense, and remove a portion of the spectrum of vibrations of the instrument, in order to maintain fringe visibility; and (3) most important, they monitor the spacecraft position during the time between losing fringes on the previous science target, and acquiring fringes on the new target.

The sequence of science observations made while the guide stars remain continuously locked is termed a *'tile'*. Tiles are the basic building blocks of all SIM observations. After solving for instrumental parameters, the science data for tile comprise a set of 1-dimensional relative positions of the targets. Since the precise attitude of the science baseline must be solved for, star positions within a single tile will always be relative measurements. A-priori positions will be measured pre-launch to around 100 milliarcsec by the US Naval Observatory, to improve the speed of fringe acquisition by SIM on-orbit.

4. ASTROMETRIC GRID

Global astrometric quantities - position, parallax and proper motion - must be referred to a global inertial reference frame to be of the most scientific value. Since SIM delivers astrometry data at an accuracy far exceeding other current or planned instruments, it must construct its own reference frame. The stars in this reference frame are termed *'the grid'*, which is built up by observing a quasi-uniform set of reference stars in overlapping tiles covering the whole sky. Tile overlap allows the whole sky to be covered and astrometric parameters to be measured for the $\sim$ 1300 stars in the grid. The detailed grid design, and simulations of the expected grid performance for an assumed model of the SIM instrument, is described in detail by Swartz.[12]

4.1. Development of the grid star catalog

Grid stars for SIM must be stable against 'astrophysical jitter' at a level of about 4 μas in a single observation. At this stability level, astrometric measurements of SIM targets will be limited by the accuracy of the measuments of the target itself, with a contribution from instrument systematics. Grid stars will be observed repeatedly during the 5-year mission, for an average of about 110 measurements in each of two orthogonal orientations. The design accuracy of the grid will be 4 μas, after a 5 year mission.

Astrophysical jitter is motion - physical or apparent - of a star which is astrophysical in origin, not instrumental. For bright stars, non-uniformities of brightness across the disk of the star (starspots) can cause astrometric jitter, but since starspots also give rise to photometric variations, troublesome stars can be eliminated from the grid catalog prior to SIM launch, by precision photometric monitoring. Variability-induced movers (VIMs) are resolved double stars in which either the primary or secondary star is variable.[13] In such systems the center of light (as measured by SIM) shifts relative to the center of mass, even in the absence of any physical motion in the system. These systems can also be eliminated by photometric monitoring.

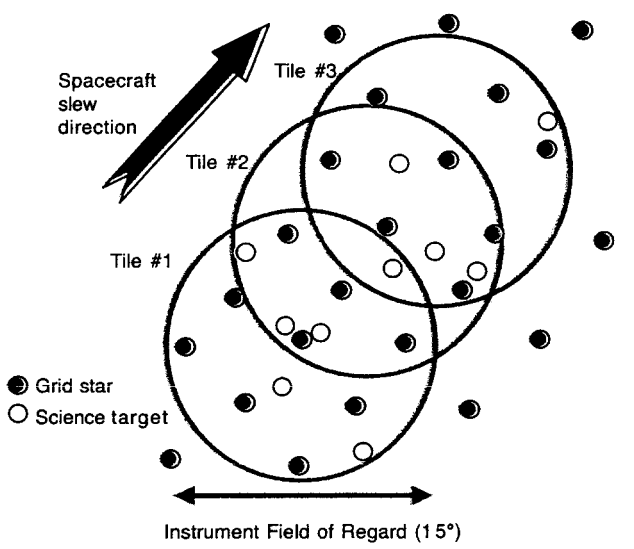

Figure 2. A representative sequence of SIM tiles, showing the locations of grid stars and science targets, and how SIM covers the sky with overlapping tiles.

A major source of jitter are short-period binary companions, over a range of masses from the low-mass end of the main sequence, through brown dwarfs, down to Saturn-mass planets. For grid stars, these are a potentially serious concern for an instrument as sensitive as SIM - but they also guarantee an amazingly rich parameter space of science opportunity. A grid catalog drawn from main-sequence stars will contain a high fraction of binary stars, and most of these produce astrometric signatures in excess of 4 μas. Candidate stars must be effectively pre-screened by precision radial velocity (RV) measurements, which sense the astrometric reflex motion of the companions.

After considerable debate, and a number of analytical and numerical studies supported by the SIM Project, the SIM grid stars will be selected from the population of metal-poor K-giants in the Galaxy. These stars are plentiful at the required brightness for SIM (around R magnitude 12), and are seen out to much greater distances (1 - 2 kpc) than their projenitor G stars. Large distance is good, because the astrometric signals of companions are reduced relative to the same stars nearby. Detailed simulations by Peterson[14] showed that a RV survey to a precision of 100 m/s would produce a yield of about 50 %; that is, a 1300 star grid catalog requires an initial survey of $\sim$ 2600 stars. Only about 6 % of the screened grid would be contaminated by binary systems missed by RV screening, an acceptable level for SIM.

4.2. Observing the grid

The grid stars will be observed at regular intervals during the 5-year SIM lifetime. The entire sky, minus an exclusion region centered on the Sun, will be covered about 22 times, in a pattern of overlapping tiles (Fig. 2). Allowing for overlap, grid stars are observed an average of $\sim$ 100 times in two orthogonal orientations, with successive 'visits' being roughly evenly spaced in time. Outside of a band around the ecliptic plane, for which there will be fewer observations, the sky coverage at the end of 5 years will be very uniform. There are a very large number of ways to conduct these observations, and they represent a complicated trade between several factors: (1) minimize the time necessary to observe and maintain the grid: this is time that is spent not doing science targets; (2) minimize systematic effects in the ultimate grid catalog from the mission - for instance 'zonal errors' in which errors in grid star parameters are correlated over certain angular regions of the sky can have a serious impact on the science; and (3), allow for unmonitored drifts in the critical instrument parameters, most notably the length of the science baseline.

This parameter space is being explored by a large numerical simulation.[12] One complete scan of the sky (a 'campaign') takes about 10 days, if done in a regular pattern of pointings, e.g. in a spiraling fashion, which seeks to improve observing efficiency by minimizing the size of slews between successive tiles (Fig. 3*a*). Individual slews would average about 7°. However, this was shown to interact unfavorably with unmonitored instrument drifts. (Thermally induced drifts which are tracked by the on-board metrology system can be straightforwardly removed in the analysis[15]). A slight modification (Fig. 3*b*) presents a more-rapidly changing orientation with respect to the Sun.

A third approach is to add a degree of randomness, which leads to a strategy termed the 'ball of string' scheme. In this scheme, the trace of slew directions on the celestial sphere resembles a ball of string. This minimizes the buildup of zonal errors by randomizing the unmonitored instrument errors. Individual slews are still limited to about 7°, as in the spiral scheme, but the slew direction is changed, quasi-randomly, on a scale of $60 - 90°$ along a great circle arc. Sun-avoidance is a major constraint (objects can be viewed no closer than 50° to the Sun), but over the course of 5 years, the entire sky can be well-covered, albeit more densely away from the ecliptic plane. There are many realizations of the 'ball of string' schedule for the grid, most being roughly equivalent in performance. Other considerations can therefore be applied, in particular maximizing science efficiency (Section 7), taking into account the sky distribution of science targets, and the desired visit schedule for each target.

4.3. Quasar frame tie

SIM must define its own reference frame, bacause its internal accuracy will far exceed the best existing reference frame, the International Celestial reference Frame (ICRF), as adopted by the IAU. The ICRF is defined by compact radio sources observed with Very Long Baseline Interferometry (VLBI), and it has an internal accuracy

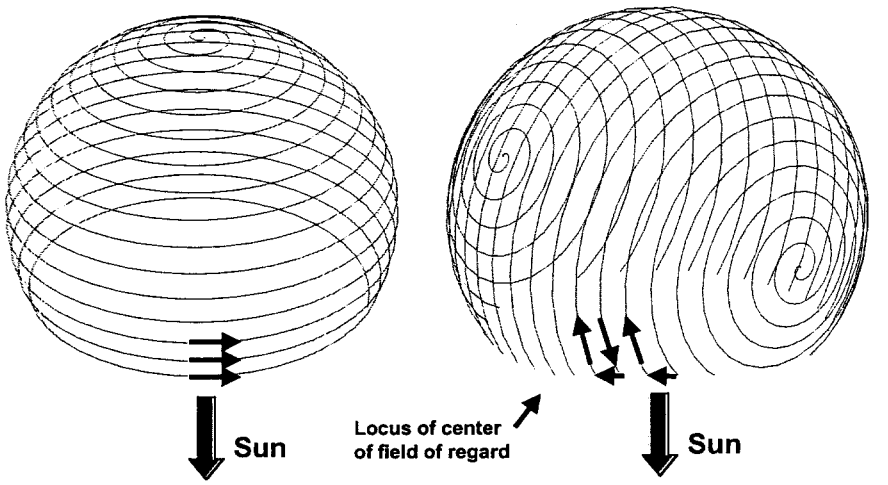

Figure 3. Scanning patterns for observing the SIM grid. The curves represent loci of the instrument pointing direction as a function of time. Sky coverage, in any given season, terminates at the edge of a Sun-avoidance cone. Scans (*a*) and (*b*) differ in the amount of time the instrument presents a given orientation to the Sun. A third option, described in the text, adds a degree of randomness to the pattern, akin to winding up a ball of string. A large number of such patterns exist, and the choice will be based on constraints from the widely differing requirements for each science program.

of about 100 μas.[16] SIM will observe a number of bright quasars to perform a 'frame tie' between these frames, for two purposes: (1) registration between the SIM astrometric catalog and catalogs from other telescopes and space missions, all of which are fundamentally tied to the ICRF. Absolute positions are of particular interest for comparing quasar positions measured both optically by SIM and in the radio by VLBI[17]; (2) to make the SIM reference close to inertial, by eliminating a rigid-body rotation of the SIM frame, which SIM is unable to measure.[18] An inertial frame is important for some of the Galactic structure science. Quasar candidates for the SIM frame tie will be selected for stability, and monitored from the ground prior to SIM launch.

5. WIDE ANGLE ASTROMETRY

The fundamental astrometric parameters measurable for each star by SIM are: position (conventionally referred to the mid-epoch of the mission) in two orthogonal coordinates, two components of proper motion, and parallax. Except for extragalactic targets, virtually every object observed by SIM will have measurable parallax and proper motion. To SIM, everything is moving! These five parameters suffice to specify the kinematics of stars, to the precision attainable with SIM. Gravitational interactions cause changes in proper motion, but over the 5-year SIM lifetime, only binary systems produce a measurable acceleration. For binaries, the interesting science is primarily in the orbit parameters, which can be determined relative to a local reference frame, using the narrow-angle observing mode (Section 6).

Measurement of the five global astrometric parameters requires the SIM observations to be 'tied' to the astrometric grid, since SIM can only measure relative positions of targets over its 15° field. The basic observing mode is therefore to observe a set of grid stars (Section 4) in addition to the target(s) in the tile of interest. The tile dataset obtained in this way allows the baseline attitude to be reconstructed, relative to the global reference frame, and hence the target star positions in the same frame. A representative wide-angle astrometry timeline is shown in Fig. 4. The nominal length of a tile is one hour, but can vary significantly depending on the number of science targets, and their brightness. Tiles longer than about 2 hours will require an additional set of grid star observations, to correct for instrument drift.

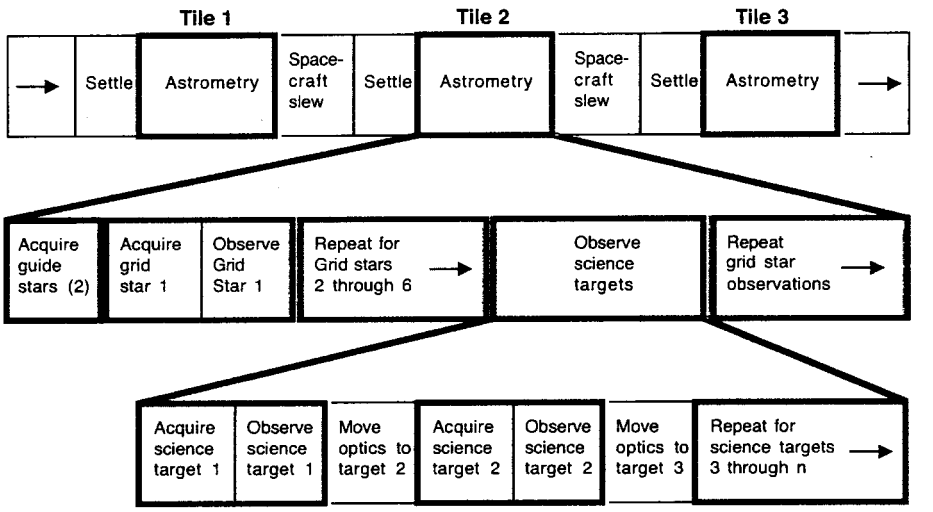

Figure 4. Timeline of SIM observations performed in a typical wide-angle tile. All accessible grid stars in the tile (normally 6 - 7) are observed, followed by science targets. To optimize the use of SIM mission time, the tile order, and the sequence of targets within each tile will be optimized to minimize the slew and setup overhead.

Since wide-angle science targets require associated grid measurements, an efficient way to schedule is to observe each science target each time the target appears in a grid tile, as part of the grid 'campaign' sequence. Targets inserted into grid tiles in this way incur very little additional setup time - only a short slew of the siderostats and delay line to acquire the new target, a procedure that takes of order 30 seconds. This method has the effect of lengthening the time for one campaign from $\sim$ 10 days to $\sim$ 40 days, with a corresponding increase in the average length of a tile observation from 15 minutes to about one hour. This is fine, since the SIM instrument design currently carries a specification for unmonitored instrument drifts over a timescale of one hour. Simulations of the expected science target accuracy for this observing scheme are now underway. To first order, science targets measured to an accuracy comparable to that of a single grid grid star, around 10 μas, will achieve an accuracy comparable to the grid itself. More accurate individual measurements are possible, by increasing integration times, and by observing the target more frequently than the grid. For bright objects the performance crosses into a regime limited by grid star accuracy, not the science target measurements. For lower desired accuracy, or for very bright targets, the star can be skipped for some fraction of the available grid tiles in which it appears.

6. NARROW ANGLE ASTROMETRY

SIM observes in a narrow-angle mode to perform relative astrometry between targets close together on the sky (within a $\sim 1^\circ$ diameter circle) to higher accuracy than can be achieved over the whole sky. This mode is used wherever the science goal requires relative, not absolute astrometry. Examples include planet detection, determining orbital elements for stellar binary systems, and structural variability in active galactic nuclei.

From an instrument viewpoint, narrow-angle astrometry differs from global astrometry (Section 5) only in the way that the 'tile' observations are constructed. A typical narrow-angle program comprises observations of a single tile, normally with the target of interest at the center, repeated many times over the course of the mission. Fig. 5 shows a representative narrow-angle tile. Grid stars are observed along with carefully-selected reference stars close to the target. Grid star data, combined with parameters for those stars derived from the grid solution, serve to determine the length and orientation of the science baseline to an accuracy required to analyse the narrow-angle data. Grid stars also serve to eliminate errors in the local reference frame which could cause a spurious rotation rate. Such errors cause targets to exhibit a spurious angular acceleration, mimicking the signature of a long-period planetary companion.

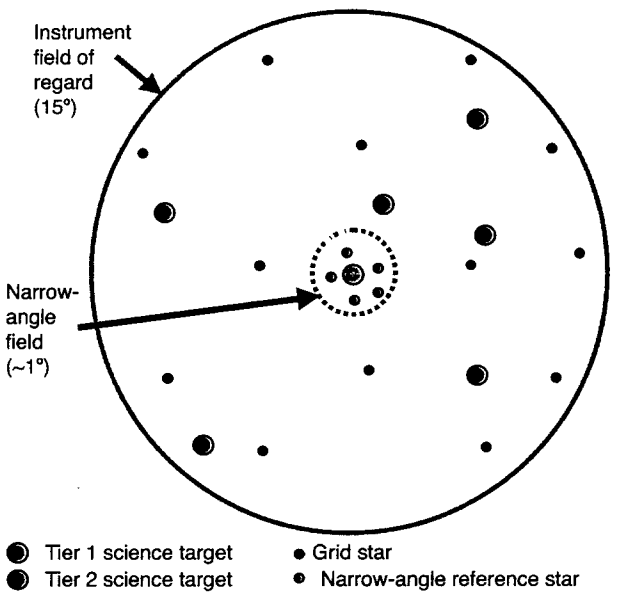

Figure 5. Science target field for narrow-angle astrometry - the mode used for planet searches. The primary ('Tier 1') target is placed at the center, with 4 - 6 'local' reference stars roughly symmetrically disposed around the SIM target within a radius of $\sim 1°$. Grid stars are observed to determine the baseline attitude, and to suppress non-inertial rotations of the frame defined by the local reference stars. 'Tier 2' targets for planet searches can be efficiently observed within the tile, to less precision.

Tile timelines (see example in Fig. 6) are designed to reduce the contributions from untracked instrument errors, that is, errors that remain after all known instrumental effect have been calibrated. Calibration may include tracking the time-history of certain quantities, like the baseline length, over many tiles, and performing an interpolation during the tile of interest.

The photon noise contribution to the astrometric error from the target itself, and the local reference stars determine the duration of each individual observation. For planet-searching, a typical duration is $30 - 6$ s, since the target and reference stars are bright (10 mag). Instrument errors affecting the measurements fall into two general classes: field-dependent (varying with instrument pointing within the field of regard) and time-dependent (any of several kinds of instrumental drift), and these are expected to be largely separable effects. To reduce field-dependences, the reference stars are chosen as close to the target as possible, subject to the availability of suitable choices. To reduce time dependence, the observing sequence comprises a series of rapid alternations ('chops') between the target and each reference star in turn. Errors causing a linear drift of astrometric position are greatly reduced compared to doing long integrations on each star separately. They are further reduced by choosing reference stars symmetrically disposed about the target star. Experiment design for mitigation of drift terms bears many similarities with techniques used by single-dish radio telescopes operating in total-power mode.

For a nominal 1-hour observation, SIM is designed to reach an accuracy of 1 μas in a reference frame defined by the local reference stars. During the mission, a total of 25 - 50 visits to the tile will be made, yielding an effective positional accuracy of around 0.2 μas, allowing the measurement of orbital parameters for orbits with semi-major axes on the order of 1 μas.[19] This is sufficient to detect an Earth-mass planet in a 1-AU orbit around one of the nearest stars, if such a planet exists.

A narrow-angle tile involves considerable 'overhead' due to the reference stars, in the sense that the target duty cycle is less than 50 %. Additional 'Tier 2' targets can be added to the timeline at little additional 'cost' in observing time. These will be less accurate (~ 4 μas rather than 1 μas) but many more targets can be done; the science goal is to collect statistics of a wider sample of planetary systems.[1] Tiles could be further generalized

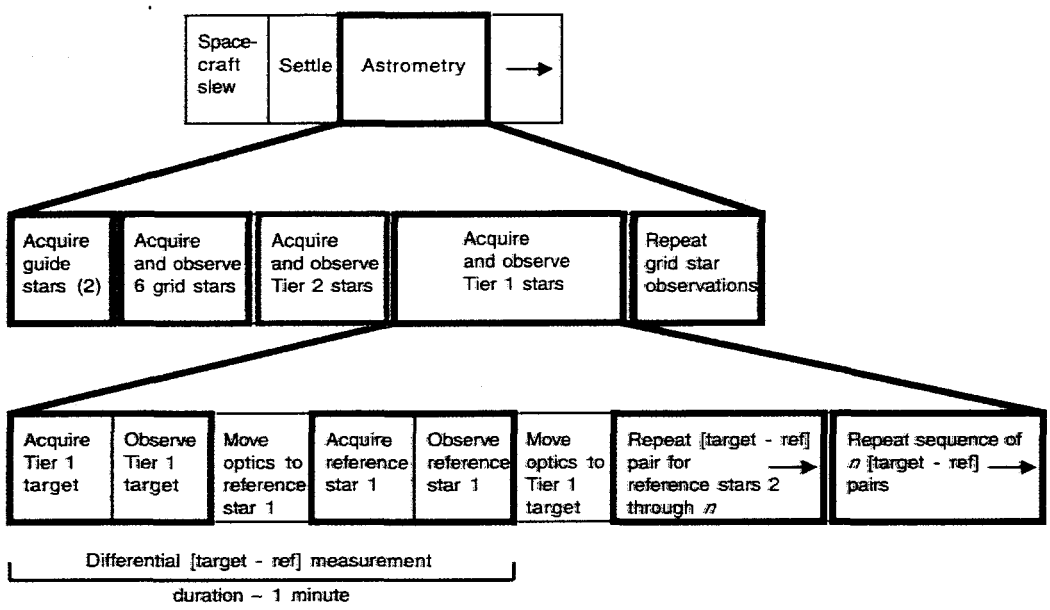

Figure 6. Representative timeline of narrow-angle SIM observations performed in a local reference frame. Observations of the 'Tier 1' target, and nearby reference stars are done in a chopping mode. This scenario, and many similar variations of it, seek to minimize the contribution to the astrometric error due to untracked instrument changes as a function of angle (small field) and drifts in time (rapid switching). Tier 2 targets would be observed before or after Tier 1.

to include global astrometry targets also; grid observations would be repeated at the end, if the total duration exceeds about one hour. This minimizes the total number of tiles that SIM must observe, which improves efficiency by avoiding unnecesary slews, and improves overall accuracy by reducing the number of instrument parameters which must be solved for.

7. SCIENCE SCHEDULING

Scheduling SIM for efficient scientific use of its 5-year mission presents some interesting challenges, because it combines considerations derived from both 'observatory class' instruments and survey missions. SIM is a 'pointed' instrument, like most ground-based telescopes, and space instruments such as HST, Chandra, and SIRTF. However, because most of SIM's science is derived from the time-dependence of astrometric positions over periods which may range from days to years, data for most science programs are spread throughput the entire mission. SIM therefore does not lend itself to scheduling in cycles in the manner of HST or Chandra.

SIM shares some characteristics with survey missions like Hipparcos,[4] which required the preparation of an input catalog before launch, which defined the science program well in advance of any data being received from the mission. SIM requires an input catalog also, because the entire 5-year mission must be laid out, to some level of precision, before launch. This is because of the synoptic nature of the SIM data products. However, in contrast to Hipparcos, a great strength of SIM is its freedom to point at any target at any time that does not violate its operational constraints.

7.1. Scheduling Constraints

The main constraint is sun-avoidance: to ensure a stable thermal environment, sunlight never enters the 'top' surface of the instrument.[15] To achieve this, no target can be observed closer than 50° to the Sun; for global astrometry, this is a weak constraint, since optimal parallax measurements are done when the target is $\sim$ 90° away from the Sun direction. Each SIM Key Project and Mission Scientist program has been awarded a

fraction of the observing time each year of the mission; nominally, it is evenly distributed. A typical global-astrometry target will be observed $\sim 20 - 40$ times during the mission; faint targets may require 100 visits or more. For planet-search targets near the ecliptic plane, a portion of each year is unavailable for scheduling. This compromises the ability of SIM to detect planets with periods close to 1 year, or harmonics of one year. Planet-searching over a wide range of expected periods requires a carefully planned sequence of about $25 - 50$ observations (in orthogonal pairs) with varying intervals between them.

Targets of opportunity (TOOs) are an exception to the uniform scheduling model. By definition, these are not pre-planned targets, but are inserted into the SIM schedule during the mission. Obviously, some time must be held back, or low-priority observations dropped, to make room for TOOs. Unlike an observatory scheduled in 'cycles', SIM cannot slip its schedule significantly. An observatory can issue its next call for proposals late, or reduce its scope. But if SIM slips its schedule significantly, then observations need to complete the science progams tend to 'pile up' at the end of the mission. This can be avoided by holding back a small fraction of time, and carefully monitoring the observing efficiency as the mission progresses.

While a small number of TOOs will not perturb the mission significantly, there is one class which will consume a significant fraction of SIM time. This is the microlensing Key Project (see summary by A. Gould in Ref. 2). Most of these targets will be in one specific region of the sky, and the rate of occurrence is matched to the allocated observing time: the best microlensing events identified from ground-based photometry will become SIM targets, each with a sequence of measurements over several months. These represent a challenge for the short-term SIM schedule, since they must be inserted into the timeline as rapidly as the Science Operations System at the Interferometry Science Center at Caltech (ISC) can allow. They do not present a long-term problem, because it is straightforward to allocate sufficient time in the long-term plan to avoid a 'pile-up' near the end of mission.

7.2. Observation Planning System

A key part of the Science Operations System for SIM at the ISC will be the observation planning system. While it is expected to build on the experience of scheduling similar space missions, the differences noted above mean that developing and testing the system is a large task. Ideally, the system has the following characteristics: high scientific productivity; efficient use of available mission time; simple application of multiple science-oriented criteria (including prioritization by the investigator); ease of combining science and instrument/spacecraft constraints; easy validation and constraint checking; minimize iterations necessary between different project responsibility areas; convenient interface to online archive for accounting of scheduled, observed (and failed) observations; automate scheduling and verification functions as much as possible. Perhaps the biggest challenge for the scheduling system is the merging of individual target timelines into a single schedule which meets the above criteria. Other aspects of the system can have much in common with tools that have been developed for other missions, such as the SPIKE tool for HST.[20]

The SIM target list is not known in detail at this time, but is expected to comprise more than 10000 targets. Each target has its own preferred timeline. Fortunately, for global astometric targets, the accuracy with which the five basic astrometric parameters can be measured depends only weakly on the detailed timeline, provided there is preference given to scheduling close to the maximum excursion of the parallax ellipse. Some investigators will wish to tailor their timelines, e.g., by front-loading observations to derive parallaxes early in the mission. Others will wish to improve the accuracy of proper motions by weighting their observations toward the beginning and end of the mission (albeit with some risk, should the mission terminate prematurely). This flexibility, coupled with a fairly smooth distribution in right ascension, ensures that a good, if not perfectly optimal, solution exists for the global asteometry targets. As noted above, planet-search targets are more constrained, requiring time-sampling at specific intervals.

Optimization of observing efficiency is driven by two considerations: (1) minimizing the number of tiles needed to complete the mission, by combining observations of targets within a tile whenever possible; and (2) minimizing the angular slew distance over which SIM must move between successive tiles. The first consideration is relatively straightforward to implement, once the input target catalog is known. It also improves the overall science accuracy of the mission by reducing the number of instrument orientation and other parameter needed.

(Limiting grid observations to campaigns containing only grid stars allows the grid to be done faster, but it greatly reduces the overall science efficiency).

Reducing the time spent moving the spacecraft between tiles is a harder problem. It can be regarded as a variant of the 'Traveling Salesman' problem[21] which has been extensively studied. Constraints to be factored in, besides the desired individual target timelines, include Sun-avoidance (during slews as well as tiles), instrument calibrations, and periods of spacecraft communication with Earth. Not decided at this time are less predictable constraints such as thermal management of the spacecraft, and management of the reaction control system angular momentum.

Critical to a successful observation planning system is an accurate science exposure time estimator. This tool needs to factor in the various instrument operations which must occur in sequence in order to record the fundamental fringe data, and also compute the best tradeoff between number of visits and the accuracy of an individual measurement. Prior to launch, this estimate may be good only to $\sim 10\%$, but will be refined early in the misison based on actual experience. The time estimator will be used in the short-term schedule to ensure that SIM is always 'kept busy', that is, the on-board schedule is augmented sufficiently often.

A bigger challenge for a time estimator is the long-term schedule. If overly optimistic, then too many science targets are scheduled early in the mission: these create a commitment to repeatedly observe the same targets that become impossible to meet, late in the mission. A pessimistic scheduler is better, because time is freed up as the mission progresses. If the understimate is modest, more visits can be awarded to approved programs, or new modest GO programs, or more TOOs, can be accepted. Fortunately, with some simple ground rules in place, the planning process can be smoothly regulated during the mission to keep pace with the actual return of science data.

8. CONCLUSIONS

This paper presented an overview of the operation and scheduling of SIM as a scientific instrument. Because it is very different in important respects from any other instruments on the ground or in space, it represents a completely fresh set of challenges. The SIM instrument itself presents many formidable challenges in its design and construction (see other papers in this Conference). For the technologists and engineers on SIM, it offers the opportunity to build and fly a truly unique instrument. For the scientists who will use SIM, there are unprecedented opportunities for discovery with an instrument capable of an astrometric accuracy 100 times better than the current state of the art.

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