4 FROM FRINGES TO COORDINATES

The basic observation that SIM makes, essentially the relative position of mirrors within its optical system, is far removed from the ultimate product of the mission — a star catalog accurate at the microarcsecond level. Furthermore, the operation of a space-based interferometer as an astrometric instrument is different in fundamental ways from the more familiar approach of astrometry based on imaging devices.

Delay measurements by SIM, converted into relative separations of stars, will form a highly accurate astrometric grid model covering the entire sky.

Although SIM will operate differently than imaging devices, SIM astrometry does have much in common with ground-based optical interferometers, such as the Mark III on Mt. Wilson and the Navy Prototype Optical Interferometer. SIM also builds on a long heritage of astrometry in radio wavelengths using very long baseline interferometer (VLBI) arrays.

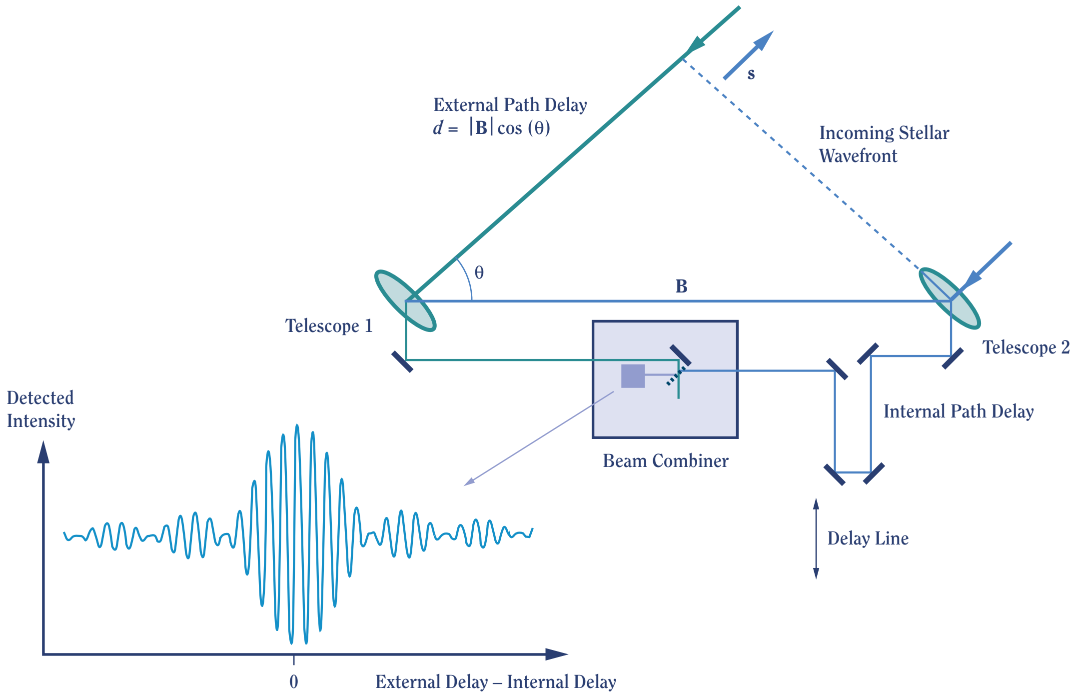
Astrometry with SIM involves three basic steps:

- Interferometric measurement of individual stars in one dimension (white-light fringes)
- Combining relative positions of individual stars over small areas of the sky into sets ("tiles")
- Combining sets of tiles in two dimensions, over the whole sky, into a self-consistent astrometric catalog (astrometric grid)

Observing with a Michelson Interferometer

A Michelson stellar interferometer operates on the principle first used by Albert Michelson in the 1920s to measure the angular diameters of giant stars. Practical considerations (such as polarization matching) often require variations on the layout, but the essential features do not change.

The Michelson interferometer operates as follows — Two physically separated telescopes collect starlight, and via a series of mirrors, bring the light to a beam combiner. The telescope axes are parallel and point along a unit vector **s** to the target. When the telescopes are used in a fixed orientation, with an articulating flat siderostat mirror to collect starlight, the combined assembly is described generically as a collector.



MICHELSON INTERFEROMETER

The optical path of starlight is shown. The response at the detector is a function of the delay difference between the "internal" and "external" light paths.

The interferometer baseline **B** is a vector quantity defined by the line joining the vertices of the two telescopes, or the pivot points of the siderostats. More rigorously, the baseline is defined in terms of the portions of the incoming wavefront (the input pupils) intercepted by the telescope apertures. The baseline **B** is defined as the relative vector displacement that causes the pupils to overlap. Baseline **B** is often expressed in units of the operating wavelength, i.e., $|\mathbf{B}|/\lambda$, because it defines a natural angular scale on the sky, the fringe spacing = $\lambda/\mathbf{B}$ radians. Light from the two collectors is combined, typically at a half-silvered mirror (sometimes confusingly termed a beam-splitter), through reflection of one beam and transmission of the other. The combined beam is focused onto a detector.

The detector senses either a bright fringe (constructive interference) or a dark fringe (destructive interference, or null), depending on the total optical path difference (OPD) between the two light paths.

A bright fringe results when the paths differ by an integral number of wavelengths. In the case of monochromatic light, fringes are visible at all OPDs and the fringe envelope becomes infinitely wide.

For the more usual case of white light, the strength of the detected signal is greatest when the OPD is closest to zero. When this condition is satisfied, the instrument observes a white-light fringe. If the OPD is too far off from zero, the interference becomes completely incoherent, and the detector simply records the mean intensity of the two beams. Typically, the instrument is sensitive over about one octave of bandwidth, resulting in approximately 2 or 3 maxima within the fringe envelope. The exact shape of the detector response versus delay is determined by the instrument passband and the fringe visibility V, which is usually represented in complex notation by its amplitude and phase: $|V|\, e^{i\theta}$.

To achieve zero OPD, the instrument must introduce an internal delay (normally by adjusting a movable delay line) equal to the geometric delay, or external delay due to the relative orientations of the star and the baseline. The expression for the delay is the delay equation

$$d = \mathbf{B} \bullet \mathbf{s} + C$$

where C is the so-called bias term — sometimes called the constant term — a (nominally) fixed instrumental offset between the true and the measured delay.

In the case of a single star, a single-pixel detector is sufficient to extract the fringe visibility amplitude. The extraction of visibility phase requires additional data, derived from delay modulation applied to one arm of the interferometer. The detected signal is read out synchronously with the modulation, and the data combined to yield the (complex) fringe visibility.

If a two-dimensional imaging detector is used, the resulting image is of a small area of sky convolved with the Airy pattern of one of the collectors. However, the image brightness is modulated due to the interference between the two input pupils. In a Michelson interferometer, the astrometric signal is in the phase of the fringe visibility, as derived by delay modulation. Astrometry is not performed using the precise position of the star's Airy pattern on the detector. Imaging devices, including Fizeau interferometers (partially filled apertures), use the image position.

When a Michelson interferometer is used in an imaging mode, the detector records a single (complex) visibility, or (u,v) point, on a single pixel. An image is derived from Fourier transforming the (u,v) data. A multipixel detector is not required for this mode.

A bright fringe results when the paths differ by an integral number of wave-lengths.

SPACE-BASED VS. GROUND-BASED INTERFEROMETERS

There are two key differences affecting the way space-based and ground-based optical interferometers are operated:

- Disturbances caused by viewing through Earth's atmosphere. The sensitivity of a space-based system is limited by instrumental stability and the size of the collecting optics. There is no externally imposed timescale for performance, in contrast to ground-based observations, which have to cope with pathlength and angle fluctuations due to viewing through the atmosphere.

- Determination of the interferometer baseline vector. On the ground, the instrument is built so that the baseline follows Earth's rotation to high precision — it is rigidly mounted to the ground. A ground-based instrument measures a set of stars in succession while Earth rotates. The delay measurements are combined with knowledge of the interferometer baseline vector at the time of observation. These measurements directly yield angles between stars anywhere on any part of the sky that is accessible to the instrument. Positional accuracy is determined by several factors, the most important of which are (1) accurate internal delay measurement, (2) knowledge of the baseline orientation at the time of observation, (3) atmospheric refraction correction, and (4) knowledge of Earth's rotation, including precession and nutation, etc.

Still, much of the basic operation is the same for both space-based instruments and ground-based instruments, such as the Mark III interferometer atop Mt. Wilson in California and the Navy Prototype Optical Interferometer at Flagstaff, Arizona. The operation concepts for SIM are based on extensive experience with these projects.

A Michelson interferometer is a one-dimensional instrument. To derive two-dimensional positions, SIM observes with the spacecraft oriented to measure in the orthogonal direction. Strict orthogonality is not required, but accurate baseline knowledge is required.

A ground-based instrument achieves the same thing by performing two or more measurements during the night, allowing Earth's rotation to change the baseline orientation. But unlike a space-based instrument, the declination of the star and the relative placement of the collectors on Earth determine the available baselines. The (u,v) plane, or aperture plane, originally defined for radio astronomical imaging, is a commonly used construct to represent the time variation in projected baseline, in units of wavelength. An Earth-based instrument can measure wide angles, limited only by their accessibility above the horizon.

Space-based instruments obviously do not have the benefit of a rigidly rotating stable platform from which to operate. On SIM, two additional interferometers observe bright "guide" stars close to the target of interest. Tracking and delay measurements from the guide stars are fed forward to the science interferometer, providing the equivalent of an inertially stable baseline. Once the science baseline on SIM is stabilized using the guide interferometers, SIM can observe any target that is accessible by reorienting the optics. This defines a field of regard (FOR), which is 15 degrees for SIM. The set of objects observed with the science interferometer (while the guide interferometers remain "locked" on guide stars) is termed a "tile" — somewhat analogous to a plate in a Schmidt photographic survey.

Because the baseline vector is not known *a priori* to high precision — in length or orientation — astrometry is done using differential measurements of the white-light fringe delay between successive stars within the FOR. The fundamental measured quantity is the change in internal delay.

Measuring Relative Star Positions

In its simplest form, a Michelson interferometer performs relative astrometry between two stars by taking a pair of delay measurements — one for each star in turn. (The two delay-line positions are located by searching for the maximum fringe amplitude on each star.) The fundamental measured quantity is the change in internal delay Δd, which yields white-light fringes on each star. In the differential delay equation

$$\Delta d = \mathbf{B} \bullet (\mathbf{s}_1 - \mathbf{s}_2)$$

the bias term C cancels out to first order. From this equation, the one-dimensional angular distance between the two stars can be deduced, once the orientation and length of the baseline vector **B** are known. For this method to work, the baseline **B** cannot be allowed to change during the pair of delay measurements. On the ground, a model of Earth's rotation is used to remove the steady change in baseline orientation due to Earth's spin. On SIM, a pair of guide interferometers effectively provides this function, at the microarcsecond level.

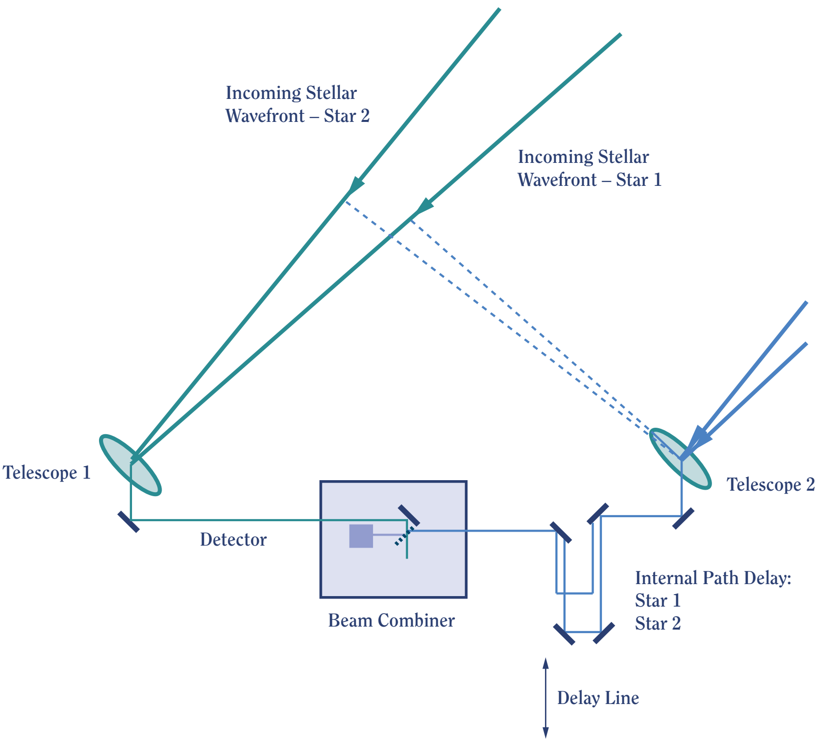
The instrument measures the internal delay corresponding to the white-light fringe, which is sensitive to two of the three components of the baseline **B**. The interferometer is sensitive only to the component of the star position that is parallel to the baseline. In the perpendicular direction, a change in the position of the star — equivalent to rotating the instrument about an axis coincident with **B** or moving the star out of the plane of the paper — produces no change in the internal delay, and hence cannot be measured. Thus, a Michelson interferometer is strictly a one-dimensional instrument. Two-dimensional astrometry requires a minimum of two measurements with nonparallel baselines. SIM will be scheduled so that every one-dimensional star measurement will be paired with a second "visit" with the baseline oriented (approximately) perpendicular to the first. Setting the orientation position angle to high precision is not required; the angle is derived *a posteriori* to a precision required for accurate two-dimensional astrometry.

Measurements of the baseline length and OPD must be made in the same-length units. Because the final products are dimensionless angles, the actual units are unimportant. Conceptually, the central wavelength λ can be used, but in practice it is convenient to use the fundamental reference of the laser metrology system used for the actual length measurements. By using a single laser to define the wavelength scale, the measurement of **s** is, to first order, unaffected by metrology drifts.

Tiling the Sky

Fundamental to SIM's design is the measurement of ultraprecise OPD of stars within a relatively small field of view. The measurement of wide angles — defined as larger than the SIM field of regard of 15 degrees — is accomplished by repointing the spacecraft, acquiring a new pair of guide stars on the guide interferometers, and observing targets that are accessible in the new orientation.

This leads to the most important concept in astrometry with SIM — the astrometric "tile." A tile is defined as the set of stars observed with the SIM spacecraft inertially pointed (by means of the guide interferometers locked onto a given pair of guide stars). Within a tile, the differential delay equation (see above) applies. In the data analysis, (relative) instrument parameters are solved for at the microarcsecond level. When moving



MICHELSON RELATIVE ASTROMETRY

If baseline length and orientation are known, the astrometric observable ($\mathbf{s}_1 - \mathbf{s}_2$) *can be deduced directly from the relative delay difference between the stars.*

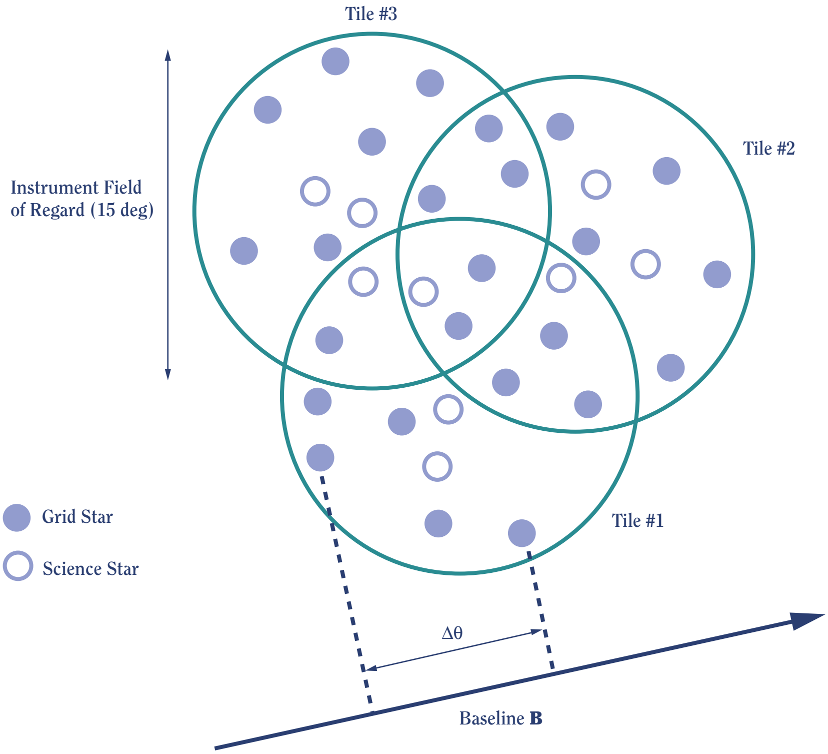
between tiles, the magnitude of the instrument rotation between tiles is not measured to high accuracy, and indeed, precise pointing of the instrument "boresight" is not required. The instrument orientation is reconstructed in ground processing.

Because SIM's basic set of star measurements is a tile with a 15-degree field, it covers the sky in a manner analogous to astrometry performed with a wide-field Schmidt telescope — namely, by a series of overlapping plates, or tiles. This method is very different from the long, narrow, great-circle strips of the Hipparcos mission or the proposed GAIA mission. Adjacent tiles overlap each other to establish relative object position and geometric continuity. As the interferometer is necessarily a one-dimensional measurement device, the available sky (4π sr minus a Sun exclusion zone) is traversed twice in two quasi-orthogonal baseline orientations to provide isotropic measurement errors.

Astrometric Reference Grid

Tiles are linked together by stars in the overlap region, thereby covering the entire sky with a systematic, interlaced, brickwork-like pattern of discrete pointings. Within each tile, SIM will observe science targets, but will also observe grid stars. The purpose of the grid stars is only to link the tiles together, and thereby to serve as links to an astrometric reference frame. During observations of a "science tile," a minimum of four grid stars is observed along with the science targets, to tie the tile into the global astrometric frame. The grid stars will be selected to cover the sky uniformly, so that in any direction, there are approximately 12 stars within the SIM field of regard. This number of stars is necessary to allow several stars in common with adjacent tiles — the key to SIM's wide-angle astrometry. SIM's astrometric reference grid will comprise a set of observations of approximately 3,000 reference stars over the entire sky. The catalog will have an internal accuracy of 4 microarcseconds or better — exceeding two orders of magnitude more accurate than the current standard for precision, the International Celestial Reference Frame (ICRF).

The SIM astrometric grid catalog will be made internally consistent by performing a global least-squares solution — on the entire set of grid star measurements, over the life of the mission — for the astrometric parameters (star positions, parallaxes, and proper motions) and instrument parameters (baseline length, orientation, and bias term, for every tile). An input star catalog will provide *a priori* star positions at a level of 0.1 arcsecond or better. An onboard star tracker will measure the orientation of the spacecraft orientation to a few



GLOBAL ASTROMETRY
SIM's astrometric "tiles." Grid stars tie the tile data into the global astrometric frame.

arcseconds. These parameters will be used as initial estimates for the least-squares solution.

The grid astrometric reduction is made by a direct sphere solution strategy. An *a priori* model for the five basic astrometric parameters of each object (position, motion, and parallax), combined with instrument models (baseline lengths, attitudes, bias terms) is fit to the measurement set from the grid observations. Simulation programs have been created to study the performance of SIM grid reductions parametrically with instrument performance, mission design, and astrophysical parameters via Monte Carlo techniques.

Grid Campaigns

For instrumental reasons, SIM will observe the astrometric grid in dedicated campaigns, with approximately four and a half campaigns per year during the life of the mission. The observing sequence will be optimized to minimize the mission time devoted to the grid while maintaining the required grid accuracy.

One scan pattern being evaluated — termed the "orange-peel" scan model — starts at the rim of the Sun exclusion zone and systematically proceeds in a sequence of circles out to the anti-Sun direction. This circle sequence is then reversed with the orthogonal baseline orientation, so the final circle of tiles is again at the periphery of the Sun exclusion region. SIM can complete an orange-peel sky coverage in about 20 days.

Roughly four and a half orange-peel campaigns will be required per year to achieve suitable reference grid performance, requiring no more than about a quarter of mission observing time. By repeating the orange-peel scans centered on the mean Sun position for the scan, no part of the sky goes unobserved for more than one scan cycle due to Sun exclusion. This is an important feature for maintaining high accuracy for the grid over the whole sky. In simulations, the overall grid accuracy is only very weakly dependent on ecliptic latitude, due to Sun exclusion. Other scanning patterns may work as well as the orange peel, but may not yield as high an observing efficiency.

Frame Tie

Ground-based instruments produce catalogs in celestial coordinates, defined in a frame that includes Earth's rotation and that defines the coordinate system of right ascension and declination. A space-based interferometer like SIM does not produce a catalog in these coordinates, but in an internal self-consistent system. SIM will define the most accurate reference frame yet — by two orders of magnitude — so any "tie" to a commonly used coordinate system, such as the ICRF, will be limited not by SIM, but by intrinsic errors in the ground-based catalog. To minimize frame-tie errors, SIM will observe 50 to 100 quasars as "tie" objects. The main purpose of these observations will be to eliminate any rotation in the SIM reference frame. Certain science objectives require this property — an example being the interpretation of peculiar motions due to spiral structure in the Galaxy. A reference frame defined only by stars would have the property of absorbing important dynamic effects into the frame itself.

For comparison with objects in catalogs made with other instruments, many (perhaps most) of the observed quasars will be radio-loud objects in the ICRF, since the ICRF is the frame adopted by the International Astronomical Union (IAU). For instance, the space-based Hipparcos catalog was tied to the radio-based ICRF through observations of a dozen radio-loud stars. Hipparcos was not sensitive enough to use quasars for

DEFINING THE ASTROMETRIC GRID

At a minimum, four reference-grid objects are required to support SIM interferometer calibration at a particular instrument pointing. This requirement, along with the 15-degree astrometric field of regard (FOR), sets a lower limit of approximately 1,000 objects in the global reference grid. However, as we anticipate some attrition among objects deemed suitable for the reference grid, prudence dictates that we carry additional objects to avoid locally insufficient grid coverage. Consequently, at present we are assuming a reference grid of approximately 3,000 objects.

The chief constituents of the reference grid will be relatively bright stars ($V \leq 12$) whose observation time is setup and metrology-integration dominated. Our strategy is to select classes of objects that would be relatively immune to anticipated sources of microarcsecond astrometric jitter — for example, early-type main-sequence stars at hundreds of parsecs, or halo K-giants. Among the reference objects, SIM will observe approximately 100 extragalactic objects (nominally quasi-stellar objects — QSOs) to establish a quasi-inertial anchor for the reference grid. Some fraction of the observed QSOs will be radio-loud to facilitate a SIM optical–VLBI radio frame tie.

The SIM Project has initiated a program of observation and theory to address the selection of suitable grid stars. A NASA Research Announcement (NRA) in 1998 is supporting six observational programs. In this area, the SIM Project anticipates supporting research in this area for several years. The selection of grid stars encompasses a number of challenging related scientific questions — for instance, the frequency, formation, and evolution of binary systems.

SIM has the capability to perform narrow-angle astrometry over small fields at an accuracy of 1 micro-arcsecond.

its frame tie. Quasars are much preferable to radio stars as tie objects, because they are expected to be much more stable astrometrically. For Hipparcos, radio stars proved adequate to register the frames at a level of about 20 milliarcseconds, and a rotation rate of about 1 milliarcsecond per year.

This frame tie will be limited by the radio observations, not by the optical astrometric catalog. Improvements in the ICRF prior to SIM's launch should allow a tie at a level well below 100 microarcseconds. Positions in the ICRF are limited by ionosphere and troposphere fluctuations, but more fundamentally by changes in radio source structure at submilliarcsecond scales.

Wide-Angle Astrometry

While the SIM grid is scientifically important in its own right, primarily with respect to reference frames, its main function is to enable wide-angle astrometry. The grid allows SIM, which is a relatively narrow-angle instrument, to measure absolute parallaxes and proper motions.

Much of SIM's science program involves wide-angle measurements, the most obvious being parallaxes. A parallax can be thought of as a wide-angle measurement in the sense that the maximum parallactic displacement occurs when the ecliptic longitude of a star is 90 degrees or 270 degrees. A star at 0 degree or 180 degrees shows zero parallactic displacement. Therefore, a parallax measurement is fundamentally a measurement over a 90-degree angle.

A typical tile observation for a wide-angle project will therefore include several grid stars to "tie" the science target(s) to the astrometric reference grid. Depending on the length of the tile observation, these grid-star observations might be interspersed with science targets. Long observations may require a second set of grid stars observed at the end of the tile. This would allow any linear drifts in baseline parameters (perhaps due to residual thermal gradients) to be removed.

The grid observation tile concept serves as the prototype of all global astrometric observations with SIM — some sequence of objects is serially observed with the science baseline while the guide interferometers monitor spacecraft attitude evolution, and the external metrology system monitors spacecraft geometry evolution. However, general science observations on a local set of targets need not view a large segment of the sky. Instead, observations of the reference grid objects are used *a posteriori* to solve for the science baseline length, attitude, and bias term at each individual epoch. SIM astrometric observations of general science objects are thus referenced to the global grid model evaluated at the epoch of observation, and solutions for target astrometric parameters are made relative to the reference grid solutions using measurements taken at several different epochs. While the accuracy goal for SIM global astrometry is 4 microarcseconds in position, the inherent flexibility of SIM's astrometric mode allows individual programs requiring varying levels of astrometric performance to be tailored — thus maximizing observing efficiency up to the accuracy limits of the reference grid itself.

Narrow-Angle Astrometry

In addition to global astrometry referenced to the astrometric grid, SIM has the capability to perform narrow-angle or differential astrometry over small (1-degree) fields at an accuracy of 1 microarcsecond. SIM's differential mode is suitable for science programs where global references are not required, but the highest possible differential performance is needed. An example of use of this observing mode is the search for the signatures of planetary companions to nearby stars by looking for the gravitational tug of the planet on the parent star. In this case, neither the absolute position of the star nor its absolute proper motion is of interest. Even the angular scale ("plate scale") and the star's parallax are of secondary interest. While in practice these would be derived from the same measurements to high accuracy, in principle they can be derived with reduced precision via a separate measurement set.

The improvement in astrometric performance follows from the expectation that the dominant systematic errors in SIM astrometry will be field-dependent errors, most notably in the metrology fiducials. In the prototypical narrow-angle program, an ancillary set of reference stars within about 1 degree on both sides of the target science is observed in conjunction with the science target(s). SIM would observe available global reference grid objects to estimate interferometer attitude, length, and bias term. All the observations at a given epoch are done within a single tile, as defined above; changes in the "science" baseline are monitored with a single set of guide stars. A careful choice of reference stars and an exact observing sequence will limit the effects of certain classes of systematic errors in delay measurement. The objective of 1-microarcsecond relative astrometry is achieved over approximately 1 hour by repeated measurements of the target star and narrow-angle reference stars.

The global reference grid observations constrain interferometer parameters such as scale and rotation, but the astrometry of the narrow-angle references and science target(s) is estimated independently through traditional differential astrometry techniques. Residual scale errors due to finite accuracy of the wide-angle references are reduced by the ratio of the wide- and narrow-angle field sizes. Since all the measurements are relative, the local reference stars must be stable to the same order of accuracy as the desired signal, so using more than one reference allows for the possibility of a similar signal (such as a binary signature) in one of the reference stars.

Data Reduction Strategy

Science processing will be performed at the Interferometry Science Center (ISC) located on the campus of the California Institute of Technology. Science data cataloged and archived at the ISC will be available 24 hours per day through a communications network, along with necessary ancillary information for browsing and data transfer. The SIM Science Team will provide direction as to the distribution and availability of all science data, and archival data formats will conform to standards set by the Science Team. It is expected that some of the scientists writing analysis software for SIM with general applicability will make this software available through the ISC.

When SIM takes data, it gathers time-stamped delay-line positions, fringe patterns, metrology data, and star-tracker information, as well as a host of other information describing the detailed time-evolving state of the instrument and the spacecraft. In converting these measurements generated on board the spacecraft to sky coordinates, other data are also needed: spacecraft position and velocity relative to the solar system barycenter, the locations and velocities of all significant gravitating masses in the solar system, and a fully closed grid model based on earlier observations.

A wide-angle astrometry experiment will measure the delay-line positions for a science target with two nearly orthogonal baseline orientations using two sets of guide stars. At least four grid stars need to be similarly observed with the same guide stars and orientation to calibrate the instrument. Therefore, at least 20 individual pointings of the science interferometer are needed.

The goal of the data analysis is to recover **s**, the direction to the target in the inertial reference frame defined by the grid. In obtaining **s**, the following steps take place:

1. The spacecraft slews to an orientation expected to maximize the signal-to-noise ratio of a set of differential angle measurements between the target and a set of local grid stars for reference (i.e., within the same tile).

2. Fringes are acquired on each grid star and the science target in turn, with the delay-line positions yielding the white-light fringe as the primary observable. These delay-line measurements include instrumental terms, in particular the so-called bias term. By using the same interferometer for all the angle measurements, this dominant term drops out to first order. During these observations, the guide interferometers, which are locked onto two bright stars, maintain the baseline orientation by actuating optical elements while the spacecraft attitude-control system maintains the coarse baseline orientation.

3. The baseline is reoriented by a spacecraft slew to a nearly orthogonal orientation that is expected to maximize the signal-to-noise ratio in an orthogonal set of differential angle measurements of the target and grid stars. Step two is repeated for the new orientation, yielding a complete set of observations from which to construct the two-dimensional geometry of the target and local grid stars. A large amount of additional information necessary for reconstructing the astrometric positions of the target is recorded.

4. The data are now taken and are ready for a first reduction on the ground. A number of deterministic effects — for example, stellar aberration determined from an accurate spacecraft ephemeris and large proper motion for some targets (which, during an observation, moves the zero-delay position) — are removed, and the delay-line positions are averaged over a single pointing for each object. Following this step, the delay-line positions are in the form of two sets of averaged positions, one for each baseline orientation.

5. The pair-wise differences in these delays comprise the important observables in reconstructing the geometry of the reference stars and target, which are related to the set of star positions. It is at this point that the constant term disappears to first order.

6. Metrology and supporting data, which determine the baseline length, and star-tracking pointing information are similarly averaged to give a first guess at the baseline orientation **B**.

7. The true baseline **B** for each orientation is found by iteratively solving the interferometric astrometry equation for the science interferometer using the grid-star differential delays, a model for the grid that specifies grid-star positions as a function of time in an inertial frame, and the temporal component of general relativistic effects obtained from a relativistic solar system model.

Data analysis will recover the direction to the target in the inertial reference frame defined by the grid.

8. While the procedure for carrying out this computation for an ideal instrument is straightforward, the fact that SIM will push the state of the art in astrometric accuracy by 2 to 3 orders of magnitude means that a number of additional instrumental and systematic effects must be characterized, understood, and modeled out at this step.

9. The differential delays involving the science target are similarly calibrated using relativistic and other instrumental and systematic effects.

10. The calibrated differential delays at this point represent a geometrically consistent set of fixed or rectilinearly moving points for which various theorems apply. In other words, we now have the differential delays that would be produced by an ideal instrument taken instantaneously from a fixed point relative to the solar system barycenter at a particular time. The fact that mathematical relationships exist between these quantities leads to checks and validation of these data.

11. The calibrated differential delays are now transformed into a set of object positions (equivalently **s**) in the local coordinate system of the reference grid objects. These positions still contain general relativistic distortions arising from the particular distribution of masses in the solar system at the mean time of the observations.

12. The object positions **s** in the solar system barycenter frame referenced to zero potential are now found, taking into account general relativistic effects.

The instantaneous coordinates of an object are usually interesting only as part of a time series from which parallax, proper motion, and acceleration terms can be derived. These quantities, in turn, are related to important physical quantities such as distance, transverse velocity, and orbital parameters of interest to researchers.

To obtain these interesting physical parameters for objects at distances under 1 megaparsec requires more than a single observation (at greater distances there is no parallactic signal at all). Because SIM has a relatively small Sun-exclusion angle, an experiment to determine the parallax of an object can be optimized by choosing the proper times at which to take measurements. In an experiment to determine the periods and amplitudes of companion orbits, the times of observation can also be optimized in a way that dynamically achieves the best determination of the various parameters of the system.

On this date, 16 months after launch, SIM is 24 million kilometers (0.16 AU) from Earth and receding away at a rate of about 1.7 kilometers per second. One-way telecommunication time is 80 seconds. At this point in its heliocentric orbit, SIM is 1.04 AU from the Sun, slightly outside Earth's orbit. The Sun–spacecraft–Earth angle is currently 73 degrees. The spacecraft is operating on a week-long sequence uplinked 3 days prior, and is about to complete grid campaign #5 of the mission.

00:00 to 06:00 — Conclusion of Grid Campaign #5

Measurements of targets within the remaining 12 tiles of grid campaign #5 are performed. These tiles, with 50-percent overlap, lie sequentially along the rim of the 45-degree Sun-exclusion zone. All the measurements are performed using a single baseline orientation, the orthogonal orientation having been performed previously. To view each tile, the spacecraft slews 7.5 degrees to the center of the tile, then waits 1 minute for vibrations to settle. Guide stars are acquired with the two guide-star interferometers, and guide-star fringes are found. Each grid object within the tile is then sequentially acquired and measured using the science interferometer. At this point in the mission, an average of 10 grid objects per tile is viewed, an average of approximately 2 objects per tile having been eliminated. Total time per tile averages to about 30 minutes. All data are sent from the interferometer to the spacecraft, and stored in solid-state memory for future downlink.

06:00 to 06:10 — Reaction Wheel Desaturation

In order to unload the angular momentum accumulated on the reaction wheels over the past few days, the onboard sequence now commands the reaction wheels to operate in a rate-control mode. This causes the wheels to decelerate and then maintain a constant 100-rpm level, resulting in a torque on the spacecraft, which causes it to deviate from its commanded inertial attitude. This causes the spacecraft attitude-control system to fire an appropriate set of thrusters in order to maintain the specified attitude. After 10 minutes, the spacecraft is stabilized and the reaction wheels, now at 100 rpm, are commanded back into normal operating mode.

06:10 to 06:15 — Spacecraft Slew

The spacecraft slews from its current attitude, pointing 45 degrees from the Sun, to an attitude pointing 90 degrees from the Sun, in preparation for the upcoming astrometric target. This slew takes 4 minutes, with 1 additional minute to allow spacecraft vibrations to damp out.

06:15 to 06:45 — Calibration

The instrument is commanded into calibration mode and performs a 30-minute calibration sequence. This sequence is performed periodically to calibrate the CCD detectors and the metrology systems and to verify the alignment of the optical components.

06:45 to 12:00 — Faint Astrometric Target and Concurrent Downlink

Following acquisition of guide-star fringes, four reference targets are measured using the science interferometer. The science interferometer is then aimed at the 20-magnitude primary target. In order to acquire this faint target, pointing information is fed forward from the guide interferometers to the science interferometer. Following acquisition of fringes by the science interferometer, a 5-hour observation of the target is performed. During part of this data-taking period, previous data stored in the solid-state memory is simultaneously downlinked to the 34-meter Deep Space Network antenna at Goldstone. This is performed over a 2-hour period at a rate of 0.4 megabits/second via the Earth-pointed high-gain antenna. Ranging and Doppler data taken during this telecom period will be processed to determine the spacecraft's velocity to an accuracy of 4 millimeters per second or better to correct for stellar aberration. During the 5-hour observation, the science interferometer measures four reference targets once per hour, and again at the end of the observation.

12:00 to 24:00 — Bright Astrometric Targets

The spacecraft now begins executing a series of astrometric measurements on a prioritized list of targets. This list comprises 60 objects in the 8 to 16 magnitude range. For each of these targets, the procedure is similar to that followed previously for the faint target, except that the use of angle feed-forward is not required for the brighter targets.

Instrument Operations

SIM will be operating in an Earth-trailing solar orbit. The SIM spacecraft will be launched into orbit from the Eastern Test Range at the Cape Canaveral Air Station in June 2005, using a Delta III launch vehicle. In this orbit, the spacecraft will slowly drift away from Earth at a rate of approximately 0.1 AU per year, reaching a maximum communication distance of about 95 million kilometers after 5 years. The orbit was chosen so that the spacecraft will receive continuous solar illumination, avoiding the occultations that would occur in an Earth orbit, simplifying thermal control and mission operations. Additionally, Earth obscuration of science targets will be minimized, increasing observation efficiency.

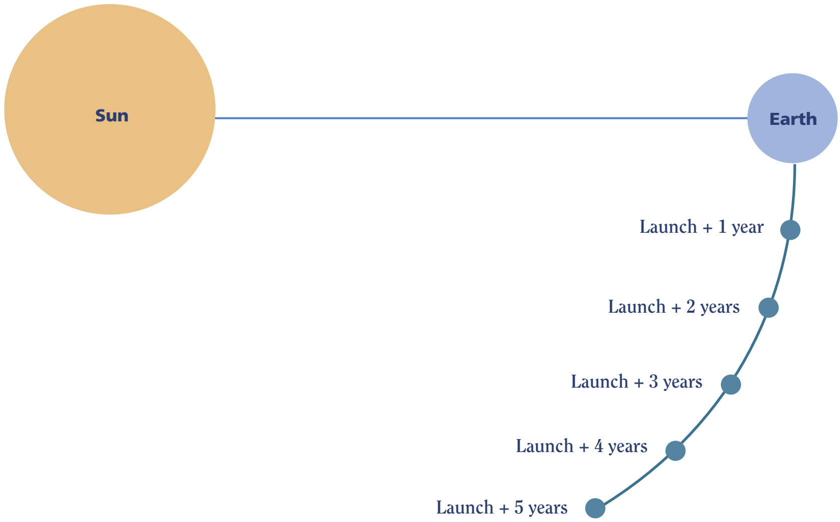
Following orbit insertion, the two unfolding sections of the spacecraft and the sunshade will be deployed. Spacecraft systems will be checked out and tracking data collected to precisely determine the actual orbit achieved. After a period of several days to allow dispersion of any contaminants, the optical covers will be opened. Checkout and calibration of the interferometer will then commence and will continue for several months. From the end of this calibration period through 2010, the SIM interferometer will perform nearly continuous science observations over the entire celestial sphere.

The spacecraft will be pointed using reaction wheels, with small reaction control system thrusters to desaturate the reaction wheels. To protect the viewing optics from heating, pointing will be performed such that the nominal viewing axis will never be within 45 degrees of the Sun. The spacecraft's velocity will need to be determined to an accuracy of 4 millimeters per second or better in order to correct for stellar aberration. This will be achieved using ranging and Doppler data obtained by 34-meter antennas at NASA's Deep Space Network ground stations during three 2-hour tracking passes every 48 hours, with the passes cycling between each of the three Deep Space Communications Complexes (at Goldstone, California; Madrid, Spain; and Canberra, Australia). Data will be recorded on board and downlinked during passes at a rate of about 0.4 megabit per second.

The goal is to operate SIM as safely and economically as possible. To this end, SIM will make use of existing multimission facilities, when it is cost-effective to do so, in order to reduce the cost and risk associated with developing new and unique systems. Examples of such facilities are JPL's Multimission Ground Data System, Multimission

SIM ORBIT TRAJECTORY

SIM will be launched into an Earth-trailing solar orbit.



Command System, and Multimission Navigation Facility. Reducing cost and risk by automated processing, use of proven off-the-shelf or locally developed software and hardware, and ease of use by the end users will be design drivers at each stage in the development of SIM's mission operations system.

SIM mission operations will be distributed. One industry partner, TRW, will be responsible for spacecraft engineering, analysis, and operation. Another industry partner, Lockheed Martin, will be responsible for interferometer engineering, analysis, and operation. JPL will perform the data management and archiving functions, and the science teams will monitor instrument health and produce the science data products. The SIM Project at JPL will be responsible for the management, control, and coordination of this distributed mission operations system. The SIM Project is also responsible for mission design, navigation, and educational outreach.