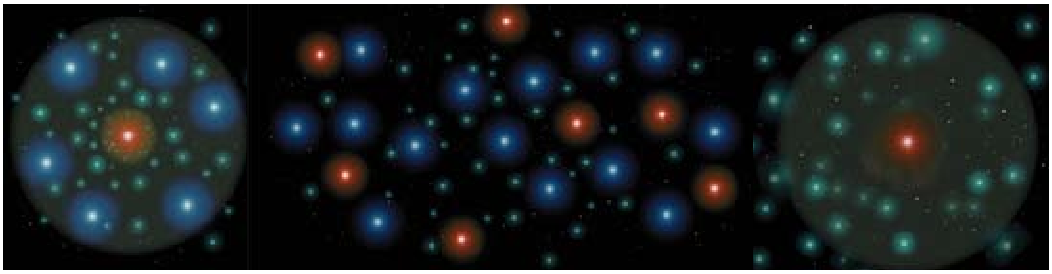
17 Observing with SIM Lite



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ABSTRACT

Making science measurements with a pointed astrometric instrument is very different from the observing modes of an imaging telescope or a spectrometer. Astrometric measurements are always made between objects, and the science is in the time-evolution of the astrometric signal. This chapter describes how the SIM Lite instrument is scheduled and operated. Astrometric observations must be carefully planned to make sure that the measurements are made between the appropriate target and reference objects, and that the observations are scheduled as part of a sequence that spreads over months or years to allow the astrometric signal to develop. Microarcsecond astrometry depends not only on optimizing observations for the desired signal, but also on scheduling the instrument in a way that minimizes systematic errors. A high-precision instrument must go hand in hand with careful experiment design.

17.1 Designing Astrometric Observations

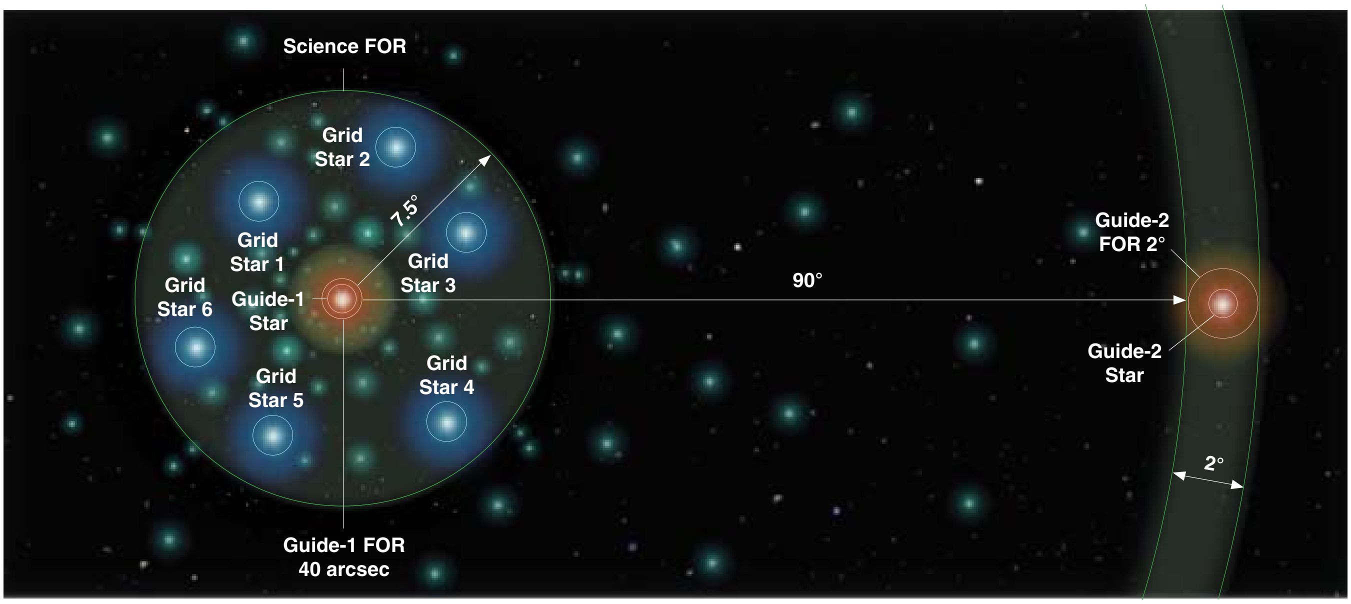
The SIM Lite instrument makes sequential measurements of the positions of stars with the science interferometer. These measurements can be processed to represent angles on the sky projected along the interferometer baseline. All astrometric signals are two-dimensional on the sky, so every science measurement requires, at some later time, a repeated measurement with the baseline oriented approximately orthogonal. Since the orientation of the baseline may be determined by many factors, including the availability of guide stars and where the instrument was last pointed, the operations do not require that the nominally orthogonal observations be paired up nor must the position angles be repeated. This complicates the analysis of placing the data into a self-consistent frame, but is not fundamental to the measurement.

All SIM 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 construction of a tile is explained below.

17.2 The Tile Concept

As explained in Chapter 16, the SIM Lite science interferometer makes sequential measurements of the path delay (through the instrument) of stars observed sequentially. Both during and between measurements, the science interferometer is held stable by continuous observations of guide stars. 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 tile, sensing the pointing of the spacecraft, and providing corrections to the attitude of the science instrument (Figure 17-1). 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. This leads naturally to the definition of the fundamental unit of observation — the tile.

Figure 17-1. A representation of the acquisition fields of regard (FORs) on the sky for the guide interferometer and Guide-2 telescope. Note that the center of the Guide-2 field is approximately 90 degrees from the tile center.



FIELD OF REGARD WITH GUIDES

A tile is defined as the set of science observations performed while the guide interferometer and Guide-2 telescope remain “locked” onto guide stars.

This definition is not just a convenience. It is intimately coupled to the fundamental design of the instrument as a device that measures differential delays.

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

A looser definition of a tile is the circular patch of sky 15 degrees in diameter centered on the guide boresight.

17.3 Target Acquisition Within a Tile

There is a sequence of activities that is executed for every tile, in order to set the instrument pointing in the desired direction and the science baseline stabilized ready to perform astrometric measurements. The slew to a new tile is done under control of the spacecraft using reaction wheels and a conventional star tracker. During slews, the science interferometer, guide interferometer, and Guide-2 telescope are not taking data.

They can, however, be prepositioned to minimize the acquisition time once they become active. First, the guide star in the guide interferometer is acquired (field of regard 40 arcseconds). The spacecraft rotates around the guide boresight until the Guide-2 star falls into the guide telescope’s field of regard, which is also 40 arcseconds. Both the guide interferometer and the guide telescope at this point lock their respective pointing loops and track the centroids of the guide stars to their nominal positions. The guide interferometer uses its two Fine Steering Mirrors (FSMs) and the guide telescope uses the fine stage of its siderostat.

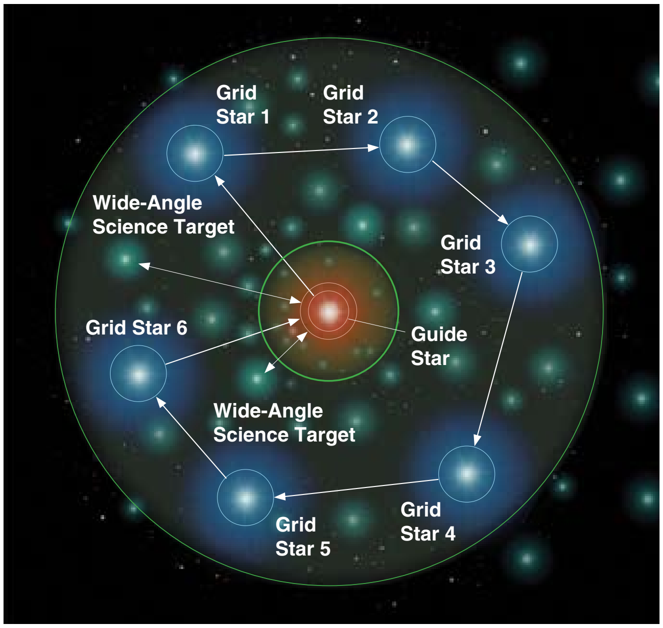
Science observations can begin once the guide interferometer has locked in both angle and fringe-track mode, and Guide-2 has its guide star stabilized.

17.4 The Astrometric Grid

Because SIM Lite can observe stars no further apart than 15 degrees — the maximum range of the siderostats — the measurement of wider angles involves the overlapping of tiles, with at least two “grid” stars in the overlap region. This is represented schematically in Figure 17-2. To minimize the overhead involved in slewing the spacecraft, the SIM Lite timeline is designed with most slews to adjacent tiles, so a typical slew is only about 5.5 degrees. Because most astrometric science depends on astrometric signals that evolve on timescales of weeks to years (exactly one year in the case of parallax), the timing of observations is very relaxed. Accordingly, the desire to minimize the slew angle can be met. The five-year observing scenario has a huge number of degrees of freedom. Finding the optimal solution (that minimizes slew time) may be almost impossible to determine. However, there exist a large number of solutions which are “very good” if not perfect.

The “grid” is a set of 1302 overlapping tiles that cover the entire sky (4π sr). Stars specifically chosen for the purpose of defining a wide-angle reference frame are termed “grid stars.” With one grid star at

Figure 17-2. The straw-man single-tile grid observation scenario, showing how wide-angle targets are integrated with grid star observations.



WIDE-ANGLE OBSERVATION

the center of each tile, the number of grid stars equals the number of tiles, namely 1302. The average separation is about 5.5 degrees, which means there are typically 6 to 7 grid stars per tile.

The SIM Project, after extensive simulation studies, selected galactic K-giant stars with a median magnitude V = 10.0 and median distance 700 pc for the grid. The primary requirement on a grid star is that its position and motion on the sky be well described by a model that includes five astrometric parameters: parallax and two components each of position and proper motion. Any (Galactic) star bright enough to be observed with SIM Lite will have a measurable parallax and proper motion, so the final reference frame must include measurements of these five parameters for every grid star. At any particular epoch, the grid is realized in terms of the positions computed from these five parameters. Ideally, these stars have no companions or other astrophysical effect which would cause "noise" in the five-parameter solution. The simulations showed that, with radial velocity (RV) screening, the K-giants will perform this task. Very few binary companions which might perturb the astrometric measurement will fail to be picked up by RV at modest precision (50 m/s). Those that "slip through" will have periods of 103 to 104 days and are not a problem for astrometry. The RV program needs three to four candidates for every star that is used in the final grid catalog.

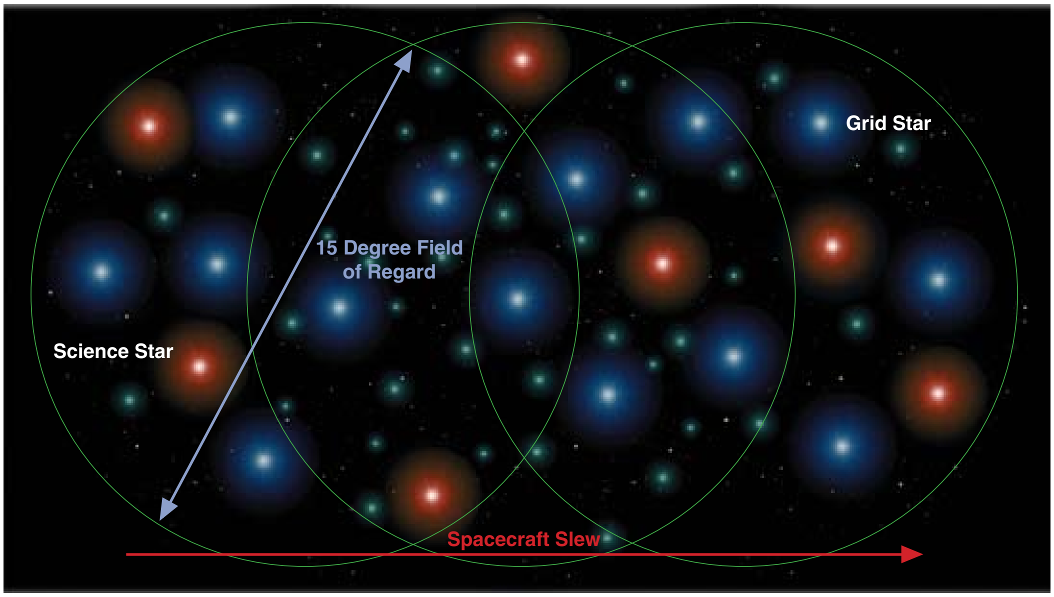
17.5 Grid Observing Scenario

The astrometric grid comprises the global solution to measurements of the 1302 grid stars during the five-year mission. The grid observing scenario is designed to serve two functions:

- To provide the best estimates of the five-parameter solutions for the 1302 grid stars.
- To serve as a “framework” upon which to support the observations of science targets.

A typical tile can be viewed in either the sky domain or the time domain. Figure 17-2 shows a sketch of a grid tile, showing the sequential observation of grid stars. As indicated, science observations occur within the “framework” of the grid. The first grid star is chosen near the tile center and is re-observed at the end of the visit, allowing subtraction of a linear drift in the instrument delay during this period.

Figure 17-3. Schematic representation of how SIM Lite covers the sky in overlapping "tiles" in a schedule designed to minimize the time spent slewing the spacecraft.



OVERLAPPING TILES

The wide-angle observing sequence for SIM Lite is built around the grid, with observations of science targets inserted into grid tiles. Normally, every grid star accessible to the instrument within a tile will always be observed. Science targets may or may not be observed, depending on the desired observing cadence and ultimate accuracy desired.

There are many ways to cover the sky efficiently (i.e., minimize the time spent slewing). One such scenario that has been studied extensively is the "orange peel." The scenario eventually used may differ, but will likely resemble this simple scheme. Optimization will be a task for project Phase C/D, implementation.

An orange peel (Figure 17-4) consists of sequential observations of 480 tiles, spaced approximately one tile radius apart, beginning in the anti-Sun direction and wrapping to the Sun's direction or vice versa. To minimize the effects of stray light, a solar exclusion zone on the sky forms the sunward boundary of each orange peel. As SIM orbits the Sun over the course of the mission, the solar exclusion zone moves accordingly, allowing the entire sky to be observable. The minimum radius of the solar exclusion zone is 49 degrees, making, at most, 83 percent of the sky available for observations at any given time.

The astrometric post-processing of grid star data solves for the astrometric parameters associated with each grid star as well as a number of instrument parameters (in effect calibrating the instrument). Over the course of the mission, there will be approximately 300,000 single-axis delay measurements covering 1302 grid stars. The number of measurements sufficiently exceeds the unknowns to allow solving for not only the five astrometric parameters per each grid star but also a number of key instrument parameters. Instrument parameters that are determined from the grid solution include the initial science baseline vector and the interferometer "constant" term at the start of each tile and the interferometer field-dependent term.

Additional instrument terms can be fitted out using this very large data set. For instance, the "field-dependent term" is a systematic bias over the science interferometer FOR and can be caused by a number of mechanisms. Since the domain of the field-dependent term is over a circle (the science FOR), it lends itself well to being described in terms of Zernike polynomials. Simulations have shown

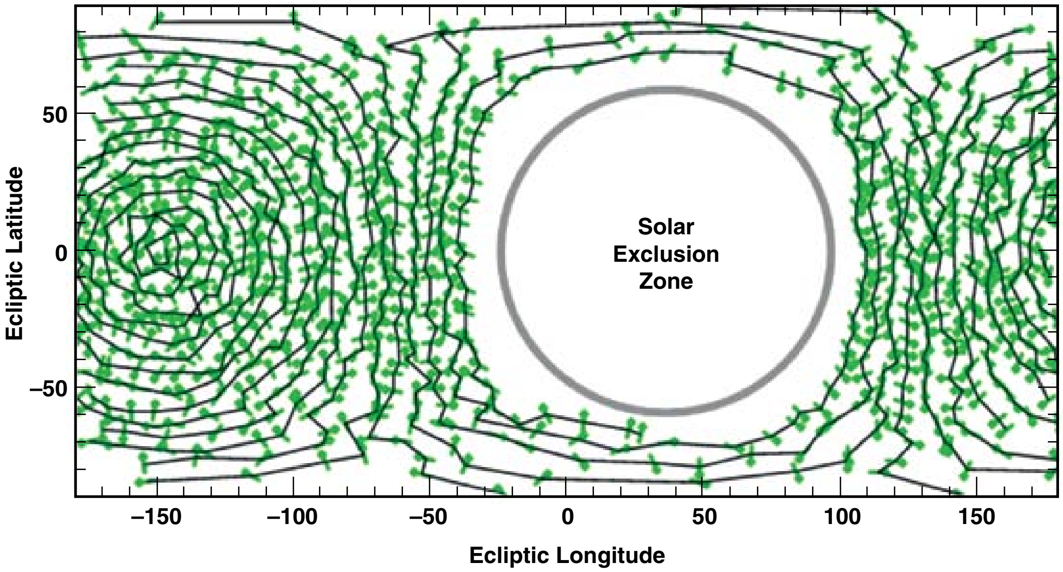


Figure 17-4. Orange peel observation sequence for an instant in time. Each observation is indicated by a green mini-arrow showing the baseline orientation. During a year, the exclusion zone traverses the ecliptic.

that the grid solution can be used to determine a piston (overall delay offset), tilt, and power error over the FOR of every tile, and higher order errors (up to fourth order in the radial component) over groups of approximately 50 tiles. Being able to calibrate these errors on the sky has allowed significant reduction of complexity, cost, and risk in SIM Lite.

17.6 The Narrow-Angle Observing Scenario

The narrow-angle (NA) observing scenario is used for the astrometric search for exoplanets and other investigations requiring the utmost performance of SIM Lite. NA observing is the most demanding of SIM Lite's astrometric applications. In this scenario, a target star's motion is measured against a set of reference stars across many visits.

As noted previously, the experiment design and instrument design are tightly coupled. In this case, the extreme astrometric accuracy is enabled by two design factors:

- Rapid switching between target and reference effectively eliminates errors cause by long-term (e.g., thermal) drifts. The relevant time scale for the instrument thermal stability is reduced to ~90 seconds.
- Differential measurements over small angles, and shared over several targets, eliminate a number of field-dependent errors that would be present in the wide-angle scenario.

The reference stars around each NA target are chosen to be astrometrically well described by position, proper motion, and parallax. As with the grid and wide-angle observations, the fundamental observing unit is a tile. Because of the demands of astrometric accuracy, tile construction must optimize the measurement sequence. Other science observations are inserted into the tile on a non-interference basis. The geometry of a typical NA visit is shown in Figure 17-5. (No other science targets are shown in this simple case.) To minimize systematic errors, the reference stars are chosen so that their individual locations and their collective barycenter are both as close as possible to the target star. On the other hand, to minimize random errors, the reference stars are allowed to be as far as one degree from the target star to increase the likelihood of brighter reference stars. During each visit, the baseline points in a single direction. In order to measure the target motion in two angles, successive visits use alternate (ideally orthogonal) baseline orientations.

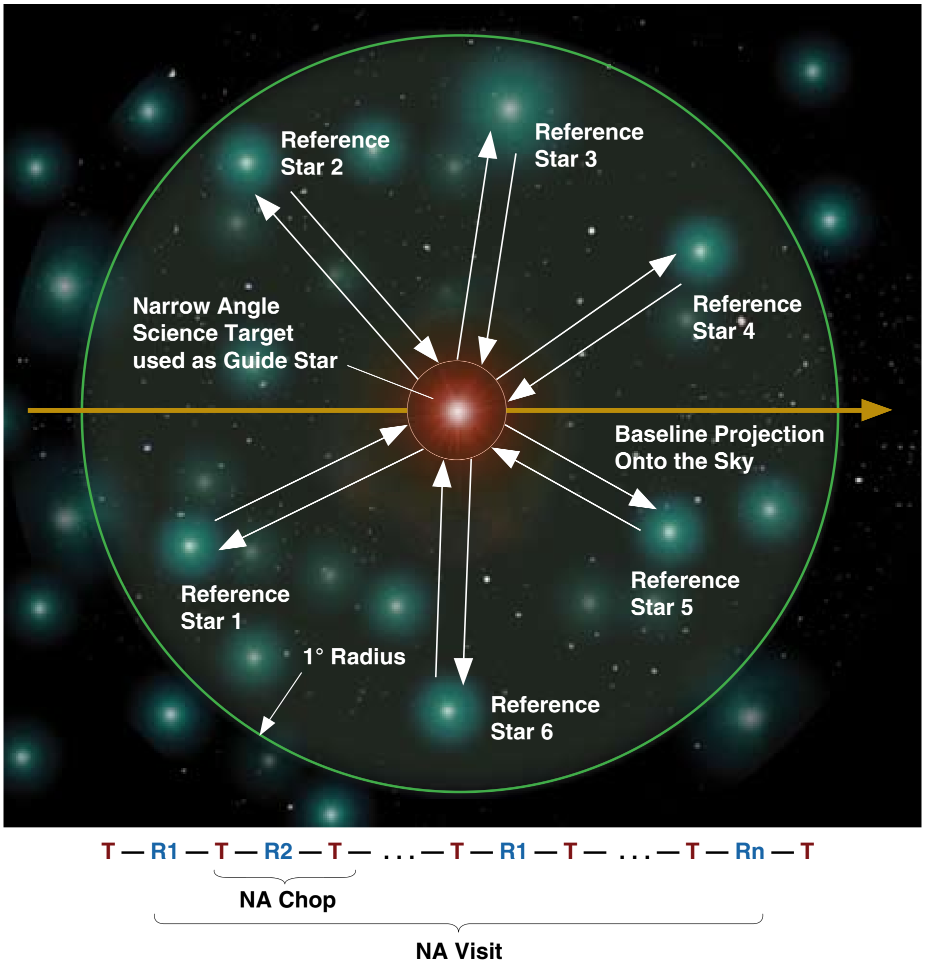


Figure. 17-5. The narrow-angle observing scenario with a target star at the center of the field of regard and reference stars within a circle of 1 degree radius. The baseline orientation on a subsequent visit would be orthogonal to that shown here.

Reference stars are not, of course, perfect reference points because of astrophysical considerations. The reference stars, like the NA target, all have proper motions, parallax, and possibly "jitter" from unseen companions. More subtly, the localized frame they define has no constraint on scaling or rotation and no clearly defined origin of coordinates.

Jitter from unseen companions can be largely eliminated by two steps taken before launch. First, reference stars are preferentially selected to be K-giants, typically at distances of about 800 pc. Thus the jitter of reference stars will generally be negligible compared to that of narrow-angle targets, most of which are less than 10 pc from the Earth. Second, candidate reference stars are vetted using Earth-based radial velocity measurements. Stars with large planets or unseen companions can be identified and rejected. As with RV screening of grid stars (Section 17.4), this process is very effective. After launch, additional steps are taken. Separate solutions will be generated in which each reference star is separately treated as the "science target," while the other reference stars and the narrow-angle target are treated as "reference stars." Simulations have shown that unseen companions that escaped notice during Earth-based vetting can be detected in this way.

The proper motions and parallax of reference stars do not affect narrow-angle performance. We fit for the parallax of both the target and reference stars, and the net proper motion of the frame is absorbed into the proper-motion solution for the target. The definition of scale and elimination of rotation is achieved by making additional observations to tie the reference stars to the SIM Lite grid. Finally, an origin of coordinates can be defined with respect to the reference stars themselves.

The basic NA measurement is the delay difference between the target and a reference star, and the analysis uses these measurements pair-wise. In the straw-man case, a target look is assumed to take 20 seconds, a reference look, 40 seconds, and the siderostat slew time from target to reference and vice versa is taken to be 15 seconds. The entire cycle of observations shown in Figure 17-5 is repeated during the visit, so that each reference star is measured three times. These are then averaged, forming a single, per-visit delay difference between the target and each reference star. The differences are collectively analyzed to determine the motion of the centroid of the reference stars relative to the local origin, which is defined to be the location of the target star. Thus, the signal is the relative motion of the centroid from epoch to epoch. For planet detection, the signal is in fact the acceleration measured across many epochs.

17.7 The Wide-Angle Observing Scenario

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

Figure 17-6 shows the observing sequence as a flowchart, illustrating how the grid and wide-angle targets are assembled into a timeline. Key to the astrometric precision are the measurements, at the start and end of each tile, of the Guide-1 interferometer guide star by the science interferometer. Since the fields are independent, both instruments can observe the same star simultaneously. This ability will be important for performance assessment during initial checkout.

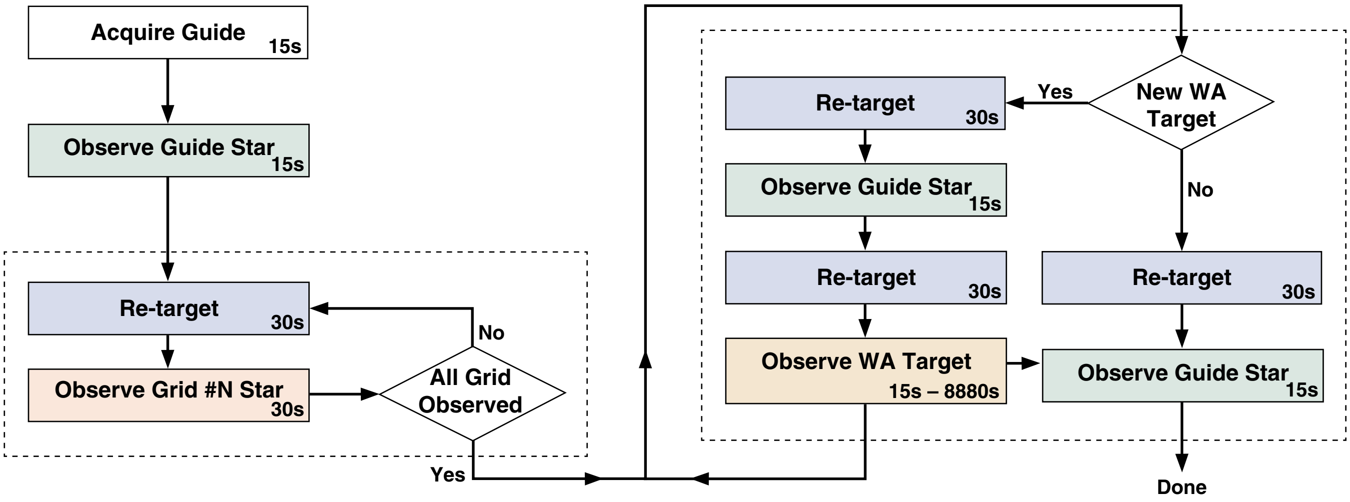


Figure 17-6. Flowchart of wide-angle observations within a single tile, showing how grid stars, guide star, and science targets are sequenced.

17.8 SIM Lite Mission Plan

17.8.1 Instrument Checkout and Science Verification

SIM Lite will be launched into an Earth-trailing solar orbit, lagging Earth by 0.1 AU/year. This orbit has been selected to minimize sky blockage and heat loading by the Earth and Moon. The trailing orbit enables one of the science experiments for SIM Lite, namely the gravitational microlensing experiment. Following launch there is a brief period, less than one month, of spacecraft checkout to ensure the health and satisfactory operation of the spacecraft component itself, followed by two months of instrument checkout. This is followed by four months for science verification, after which regular science observations begin.

The instrument checkout phase entails the initial power-up of the instrument, deployments, alignments, calibrations, and characterizations. Optics are exposed to space for the first time, after sufficient time has passed for structures to outgas to the vacuum. Initial alignment of the optics is commanded and target pointing is characterized. Tests are made of the instrument's thermal response and the effects of stray light. Exposure tables are verified.

After the instrument satisfactorily passes through checkout, science verification begins on SIM Lite. This is an intense period of testing the instrument and the spacecraft together to demonstrate they are ready for science operations. During this phase, narrow- and wide-angle astrometric measurements will be demonstrated. Differential wide-angle measurements will be made through the full orbit of a short-period binary star. Sample crowded fields will be observed, as will the effects on observations made close to Earth, the Moon, and Jupiter. By the end of this phase, the astrometric grid stars in about 75 percent of the sky will have been mapped three times (the missing portion residing in the solar exclusion zone until SIM Lite has moved through about 60 degrees of orbital longitude). This provides enough data to perform the first, very approximate, grid solution.

17.8.2 Observation Planning

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 their 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 observation requests, spacecraft maintenance, data downlinks, calibrations, and other flight activities into the schedule. After launch, during science verification, the astrometric software will be updated based on in-flight experience.

A six-week "sequencing" process is planned for SIM Lite operations spanning a two-week period. Several of these sequence planning processes will be ongoing, at different phases, throughout the mission. The initial four weeks are used by the mission operations team to prepare the science measurement commands for the instrument, calibration measurements, and spacecraft orientation commands. Additional spacecraft operations sequence commands are added by the flight team, including uplink/downlink, housekeeping, and general maintenance commands. This complete sequence is run through a spacecraft simulator for validation, then translated and uplinked to the spacecraft to begin operation a few days after receipt.

In the current plan for SIM Lite, missed observations will not be rescheduled, due to the expense of developing a scheduling and verification system capable of executing schedule changes robustly. Since most science programs involve repeated observations of each target, the loss of any particular observation will rarely be critical.

17.8.3 Data Downlink and Analysis

Science, metrology, and spacecraft data will be downlinked from SIM Lite in two eight-hour passes per week at Ka-band. All instrument data are downlinked through the high-gain antenna in no more than eight hours per week (end of mission). The remaining contact time uses the low-gain antenna for command upload, engineering telemetry, and Doppler ranging. The ranging data are required to determine spacecraft position and velocity for relativistic corrections to observed angles. The spacecraft memory volume is sized to hold data collected over a two-week period. In the event of a missed downlink, those data are preserved for repeat transmission up to two weeks after a lost downlink.

Once the data are “on the ground,” they will be funneled through standard Deep Space Network processes and transferred to NExScI. At NExScI, the data will be processed using current calibrations, metrology at the time of the observation, and other correction routines. Aberration and general relativistic corrections will be made and the astrometric grid will be applied.

The astrometric grid will first be released about half-way through the mission. A final grid will be computed at the end of the mission and much of the data will be recomputed based on this improved grid at that time.

Rigorous definitions have been constructed for each phase of the data analysis, including data product levels. Access to the instrument “raw” data will be restricted, and in any case will be of little interest to typical users. In most cases, the lowest level data product will be “regularized delays.” These data represent a self-consistent set of measurements in which the science interferometer is (effectively) fixed and known to μas precision relative to the astrometric grid. From these data, the user can derive the standard (five-parameter) astrometric quantities: mid-epoch position, proper motion, and parallax. Preliminary estimates will be provided to all users as part of the standard data products. For binary stars and planet searches, additional parameters defining the companions will be fitted to the data. These will be the responsibility of the individual investigators.

The level of science support, data product verification, visitor support, etc., for SIM Lite have yet to be determined in detail. Detailed plans for SIM PlanetQuest have already been developed, and these will be adapted to define the SIM Lite science operations system, with a view to providing science support at low cost.