INTEROFFICE MEMORANDUM

JET PROPULSION LABORATORY
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To: Richard Stoller

Subject: SIM Preliminary Astrometric Observing Scenario

Note This Memo was originally distributed Nov 24, 1996. This copy is intended for the SIM online database. If focuses on the operations issues resulting from the requirement that SIM establish an astrometric grid. Andy Boden is currently working on an in-depth presentation of the astrometric performance of grid observations.

(1) Introduction

The purpose of this Memo is to provide a description of the SIM observing scenario, as presently envisaged, for spacecraft and mission design trade studies. Since SIM is a pointed instrument, the range of possible observing scenarios is huge. However, one aspect of the mission, development of the astrometric grid, is sufficiently well-defined that we can develop a preliminary observing scenario, with a description sufficiently detailed to enable trade studies to be performed - between, for instance, Earth orbit and Earth-trailing / L2 trajectories.

The astrometric grid is critical to the science which SIM will perform, because it establishes a reference frame on the sky which is required by most of the planned science investigations. Detailed simulations of the analysis of astrometric grid data are underway (work by Andy Boden). These studies will predict, as realistically as possible, given the current description of instrument operation, the accuracy of the positions of grid stars. This accuracy is directly related to the precision of the basic instrument function - the measurement of angles between stars to high precision.

In this Memo, we present grid observing scenarios, and the mission and instrument parameters required to achieve them. Two representative scenarios are given in detail; representative in the sense that the derived parameters are close enough to those of the final scenarios to allow trade studies to be performed.

We also present an estimate of those same parameters for observations in the remainder of the mission - loosely be termed 'science observations'. Operationally, the distinction between 'grid' and 'science' is clear, as the description below indicates. Scientifically, the distinction is less clear, as there is considerable scientific interest in the astrometric grid stars. Any given star might perform a role as a grid star and a science target at different times.

(2) Definition of terms

TILE

A 'tile' represents a set of observations of stars all performed with the guide interferometers remaining locked onto a pair of guide stars. Observations of a tile are accomplished in a single pointing of the spacecraft. Sideostats and delay lines move to allow observations of targets within the FOV. In the nominal instrument operation, all science observations within a tile are done by a single interferometer, which we call the 'science interferometer' - usually one of the longer baselines.

Note that the guide stars need not be grid stars, and in general will not be, since guide stars do not have the same constraints on their selection: they must be bright, and not significantly resolved by the longest baseline.

A tile has an area equal to the field of view of the siderostats ('square' 15deg x 15deg in the current instrument design). Strictly, the FOV is bounded by four great circle arcs on the sky.

ORANGE PEEL

Refers to an observing strategy in which the sky is covered in a sequence of contiguous overlapping tiles, in a spiral pattern about an axis fixed in inertial space. In practice, the successive spiral turns are replaced by a series of small circles centered on the same axis, with radii chosen to produce the desired overlap between tiles. In the scenarios we consider here, sun-avoidance imposes a symmetry on the observations, leading to the anti-solar direction as the 'start' of the orange peel. The 'end' is determined by the sun avoidance angle.

GREAT CIRCLE SCAN

A series of overlapping tiles whose centers trace out a great circle on the sky. This is the basic element of the scanning scheme used by HIPPARCOS. In principle, 2 pi closure can be applied to observations along a great circle, thereby correcting for a scale error in the angular scale. [It is less clear that SIM can take advantage of the same strategy, due to its very different architecture.]

HIPPARCOS SCANNING LAW

Observing scenario by which the HIPPARCOS mission covered the sky. The axis defining great-circle scans was maintained at 43deg to the sun direction, and precessed about that direction with a period of 57 days. Approx 6.4 cycles were executed per year, maintaining the sun direction as the precession axis, as the sun moved relative to the star field. SIM could emulate this strategy, perhaps taking one precession cycle as the basic unit of observation (covering ~84 % of the sky). However, results from Andy Boden's grid simulation tool indicate that the 'orange peel' scanning law has significant advantages (the reasons for which are beyond the scope of this Memo).

(3) Constraints on astrometric grid observations

(a) The SIM astrometric grid must cover the entire sky to a specified precision. The current design goal is 4 uas (RMS) in each of two orthogonal coordinates; this value is a fraction R of the single-measurement accuracy of the interferometer. (Detailed simulations of the grid data reduction are being performed to determine this ratio; for the strawman scenarios below, preliminary results show that R <~ 0.50 can be achieved over the whole sky).

(b) A minimum surface density of grid stars is required. In any tile, there must be a minimum of 3 grid stars (to define scale, translation, and rotation of the field, and a baseline orientation which is also solved for). In practice, a much larger number of stars (~10) are required, because:

i) The probability that a given direction will have too few grid stars (given a quasi-random distribution), must be low;

ii) Stars may provide unsuitable as grid references, due to being resolved, have binary companions, or data are lost or corrupted, etc.

A tile, or group of tiles in which there are too few observations can suffer reduced grid accuracy and affect the accuracy of the grid on larger angular scales also.

(c) Grid observations must be repeated at intervals of a few months, because:

i) Parallax measurements require a minimum of two observations separated by a few months, ideally 6 months, appropriately phased.

ii) Stars in the sun-exclusion zone should be observed shortly after emerging from this region.

iii) Separating the effects of parallax, proper motion, and binarity require require repeated observations over a several-year span.

(d) Each tile observation must be repeated, with the interferometer baseline approximately perpendicular to the first orientation. This is necessary to ensure that the astrometric grid errors are approximately isotropic.

(d) During observation of a tile, the spacecraft attitude must not change by more than 15 arcsec, or drift faster than 6 arcsec/s. [A rough estimate of the spacecraft attitude change, due to reaction against moving delay lines in the absence of active control, is a maximum effect of ~15 arcsec.]

(4) Strawman grid observing scenario

We assume an 'Orange peel' scanning strategy, and consider two cases: (a) Earth-trailing or L2 trajectories, in which Earth avoidance is ignored, and tiles can be observed in any order [parameter set G01], and (b) low-Earth orbit, in which long slews are required to satisfy the Earth avoidance [parameter set G02]. Slew, settling, and observing times are all estimates, adequate for the purpose of designing a scanning strategy.

(a) Earth-trailing or L2 trajectory

Observing parameters (set G01):

SE	=	43deg	=	Sun exclusion angle
EE	=	80deg	=	Earth avoidance angle (i.e. no exclusion)
F	=	15deg	=	tile field of view
O1	=	0.5	=	Step between tiles (units of FOV) in 'peel' direction
O2	=	0.5	=	Step between tiles (units of FOV) transverse to 'peel' direction
TS	=	90sec	=	Observing time per star (slew + settle)
TO	=	30sec	=	Observing time per star
SR	=	1.5 deg/min	=	spacecraft turn rate
TT	=	5min	=	Time to slew between tiles
TA	=	5min	=	Time to settle on new tile and acquire guide stars ('calibrate')
N	=	10	=	Number of objects observed per tile (mean)
GI	=	91days	=	Interval between grid observing 'campaigns'
L	=	5 yr	=	mission lifetime

The above parameters lead to the following specification for the grid.

Available sky covered in one campaign	=	87 %
Total number of tiles observed	=	635
Number of grid stars	=	1833
Time per tile (slew, calibrate, obs 10 stars) = TI	=	30 min
Time to observe one campaign = TC	=	26.5 days
Number of campaigns in 5-yr mission	=	20

Fraction of campaign spent slewing between tiles	=	17 %
Fraction of campaign spent calibrating a tile	=	17 %
Fraction of campaign spent acquiring stars in a tile	=	50 %
Fraction of campaign spent observing stars in a tile	=	17 %
Fraction of mission spent in grid observations	=	29 %
Number of 7.5deg slews in grid obs during mission	=	25400

Number of grid tiles during mission	=	12700

(b) Low Earth orbit

Observing parameters (set G02):

SE	=	43deg	=	Sun exclusion angle
EE	=	~45deg	=	Earth avoidance angle (see Note 1)
F	=	15deg	=	tile field of view
O1	=	0.5	=	Step between tiles (units of FOV) in 'peel' direction
O2	=	0.5	=	Step between tiles (units of FOV) transverse to 'peel' direction
TS	=	90sec	=	Observing time per star (slew + settle)
TO	=	30sec	=	Observing time per star
SR	=	4.5 deg/min	=	spacecraft turn rate
TT	=	20min	=	Time to slew between tiles (see Note 2)
TA	=	5min	=	Time to settle on new tile and acquire guide stars ('calibrate')
N	=	10	=	Number of objects observed per tile (mean)
GI	=	91days	=	Interval between grid observing 'campaigns'
L	=	5 yr	=	mission lifetime

Note 1: EE determines the maximum time inertial pointing can be maintained before initiating a long slew to avoid violating the Earth avoidance constraint. This is obviously geometry dependent: worst case is zenith pointing, for which inertial pointing can be maintained for ~25min (assuming 103min orbit period); best case is pointing in anti-solar direction, for which there is no earth blockage.

Note 2: For this observing scenario, we assumed that most tiles would be observed for the maximum possible time, which implies a typical slew of ~90deg. Parameters O1 and O2 are satisfied by always slewing an integral number of (overlapped) tiles, in a sequence which visits each tile once.

The above parameters lead to the following specification for the grid.

Available sky covered in one campaign	=	87 %
Total number of tiles observed	=	635
Number of grid stars	=	1833
Time per tile (slew, calibrate, obs 10 stars) = TI	=	45 min
Time to observe one campaign = TC	=	39.7 days
Number of campaigns in 5-yr mission	=	20
Fraction of campaign spent slewing between tiles	=	44 %
Fraction of campaign spent calibrating a tile	=	11 %
Fraction of campaign spent acquiring stars in a tile	=	33 %
Fraction of campaign spent observing stars in a tile	=	11 %
Fraction of mission spent in grid observations	=	44 %
Number of ~90deg slews in grid obs during mission	=	25400
Number of grid tiles during mission	=	12700

(5) Science observations scenario

Science observations encompass a wide variety of observing strategies, with differing object densities and brightnesses. Example of two extreme cases are:

(i) Dynamics of stars in globular clusters. Observations in a single tile of many targets (10-100), plus grid stars. Typical star brightnesses much fainter than the grid stars. In the absence of sun/earth blockage constraints, a tile might take 5 hours to complete.

(ii) Parallaxes of Cepheid and RR Lyrae stars. In this case, the objects of interest are of comparable brightness to grid stars, and a typical tile might contain only one or two stars of interest. Observations will resemble those of grid tiles, of length ~30 min.

Of the available science time (1 - TC/GI), the observing time may be dominated by faint objects (case i). However, observations in case (ii) will dominate the number of tiles observed, which is more relevant to this Memo. Assuming case (ii) observing, we can approximate the number of tiles and slews by assuming grid observing mode for the entire mission (setting TC = GI above).

(a) Earth-trailing or L2 trajectory

Observing parameters (set S01):

SE	= 43deg	=	Sun exclusion angle
EE	= 180deg	=	Earth avoidance angle (i.e. no exclusion)
F	= 15deg	=	tile field of view
O1	= 0.5	=	Step between tiles (units of FOV) in 'peel' direction
O2	= 0.5	=	Step between tiles (units of FOV) transverse to 'peel' direction
TS	= 90sec	=	Observing time per star (slew + settle)
TO	= 30sec	=	Observing time per star
SR	= 1.5 deg/min	=	spacecraft turn rate
TT	= 5min	=	Time to slew between tiles
TA	= 5min	=	Time to settle on new tile and acquire guide stars ('calibrate')
N	= 10	=	Number of objects observed per tile (mean)
L	= 5 yr	=	mission lifetime

These parameters lead to the following specification for the whole mission:

Time per tile (slew, calibrate, obs 10 stars) = TI	=	30 min
Fraction of mission spent slewing between tiles	=	17 %
Fraction of mission spent calibrating a tile	=	17 %
Fraction of mission spent acquiring stars in a tile	=	50 %
Fraction of mission spent observing stars in a tile	=	17 %
Number of 7.5deg slews during mission	=	87600
Number of grid/science tiles during mission	=	43800
Number of science target tiles observed during mission	=	31100

(b) Low Earth orbit

Observing parameters (set S02):

SE	= 43deg	=	Sun exclusion angle
EE	= ~45deg	=	Earth avoidance angle (see Note 1)
F	= 15deg	=	tile field of view
O1	= 0.5	=	Step between tiles (units of FOV) in 'peel' direction
O2	= 0.5	=	Step between tiles (units of FOV) transverse to 'peel' direction
TS	= 90sec	=	Observing time per star (slew + settle)
TO	= 30sec	=	Observing time per star
SR	= 4.5 deg/min	=	spacecraft turn rate
TT	= 20min	=	Time to slew between tiles (see Note 2)
TA	= 5min	=	Time to settle on new tile and acquire guide stars ('calibrate')
N	= 10	=	Number of objects observed per tile (mean)
L	= 5 yr	=	mission lifetime

These parameters lead to the following specification for the whole mission:

Time per tile (slew, calibrate, obs 10 stars) = TI	45 min
Fraction of mission spent slewing between tiles	44 %

Fraction of mission spent calibrating a tile	11 %
Fraction of mission spent acquiring stars in a tile	33 %
Fraction of mission spent observing stars in a tile	11 %
Number of ~90deg slews during mission	58400
Number of grid/science tiles during mission	29200
Number of science target tiles observed during mission	18400

(6) Comments on the preliminary observing scenario

(a) The above scenarios for science observing do not include imaging. As presently envisioned, only a small fraction of the mission will be devoted to imaging. Imaging will be done in a continuous-rotation mode, for which a completely separate observing scenario must be derived. Since the constraints on the observing strategy should be no more severe than for astrometry, imaging can be ignored for the purposes of this study.

(b) In Earth-trailing or L2 trajectories, long slews can be avoided almost completely. In this analysis, a typical slew is 7.5deg. A modest spacecraft turn rate of 1.5deg/min results in 17% of grid observing time spent in slews.

(c) In Earth orbit, a much faster turn rate of 4.5deg/min results in 44% of grid observing time spent in slews, and almost half the mission devoted to the grid. A much faster turn rate would improve the overall observing efficiency: a rate of SR = 18deg/min would result in TT ~ 5min, and hence the same grid parameters as the Earth-trailing or L2 trajectories.

(d) All of the above calculations assume 2 minutes observation per object, i.e. 'setup dominated'. We assumed TO = 30s for data collection, and TS = 90s for setting siderostats and delay lines on a new star and acquiring fringes. In Earth-trailing orbit (parameter set G01), half of the grid observing time is consumed by settling; reducing TS would greatly improve the fraction of the mission which can be devoted to observing faint targets.

(e) These observing scenarios do not allow for (1) additional spacecraft functions (e.g. telemetry uplink/downlink, reaction wheel desats, etc.), (2) instrument calibrations other than the acquisition of guide stars, or (3) additional attitude constraints (e.g. solar panel illumination, earth shadow).

(f) Other scanning strategies, including the HIPPARCOS scanning law, are feasible, but less attractive for optimizing grid performance. They could easily be added to this study.

(7) Conclusions

This Memo outlines the most significant constraints on the SIM observing scenario. The scenario is driven primarily by the requirements for minimizing errors in the overall astrometric grid.

The grid observing parameter space is very large, and is the focus of a separate study by Andy Boden. However, the observing scenario we discuss (the 'orange peel') can be specified completely, allowing parameters describing it to be derived numerically from basic instrument parameters. This parameter space is large, but certain parameter combinations can be explored using an EXCEL spreadsheet.

We have identified a few parameters from the instrument and spacecraft design which interact strongly with the observing scenario, and must be included in any optimization:

Spacecraft turn velocity

Spacecraft settling time to acquire new position

Sun and Earth avoidance angles from viewing direction

Instrument calibration and settling time

(8) Credits

This memo attempts to synthesize the efforts of a number of people. Many people have studied the observing strategy for SIM. Those involved with recent studies have been Andy Boden, Rob Lock, Su Potts, John Reimer, Richard Stoller, Patty Koenig, and Ray Bambery.