GLOBAL ASTROMETRY WITH THE SPACE INTERFEROMETRY MISSION

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ABSTRACT

In this paper we will discuss the prospects for global astrometric measurements with the Space Interferometry Mission (SIM). SIM will perform four microarcsec astrometric measurements on objects as dim as 20th magnitude using optical interferometric techniques with a 10 m baseline. SIM performs both narrow-angle astrometry and global astrometry by means of an astrometric grid. We will report on sensitivities of SIM global astrometric performance and grid accuracy versus instrumental parameters and sky coverage schemes. The problems in finding suitable astrometric grid objects to support microarcsec astrometry, and ground-based observing programs that address these issues will be discussed.

Key words: space astrometry; microarcsec astrometry; optical interferometry.

1. INTRODUCTION

The Space Interferometry Mission (SIM) is a part of NASA's Origins program and NASA's first dedicated science interferometer in space. SIM is currently envisioned as a 10 m baseline optical interferometer. According to current schedule SIM will receive NASA Phase C New Start funding in 2001, and be launched in 2005. The technical objectives for SIM are microarcsec-class narrow-angle and global astrometry for sources brighter than 20th magnitude, 10 milliarcsec rotational synthesis imaging, and on-axis nulling of bright sources to observe faint environments around them. The science goals of the SIM mission are described elsewhere (Peterson 1996; Unwin 1996; Peterson 1997a).

Figure 1 shows a line drawing of the current reference design for the SIM spacecraft. SIM has seven light collecting mirrors (siderostats), from which three arbitrary interferometric baselines can be simultaneously formed. (The extra siderostat is included for fault tolerance and imaging performance.) Of the three interferometric baselines, two are nominally used to monitor spacecraft attitude stability and pathlength and pointing control signals as the third baseline collects science data. Integral to the SIM concept, integrated internal and external metrology system monitors the relative system geometry and internal pathlengths. A synoptic view of the SIM mission concept is given in Table 1; a more detailed architectural description can be found in Shao 1996.

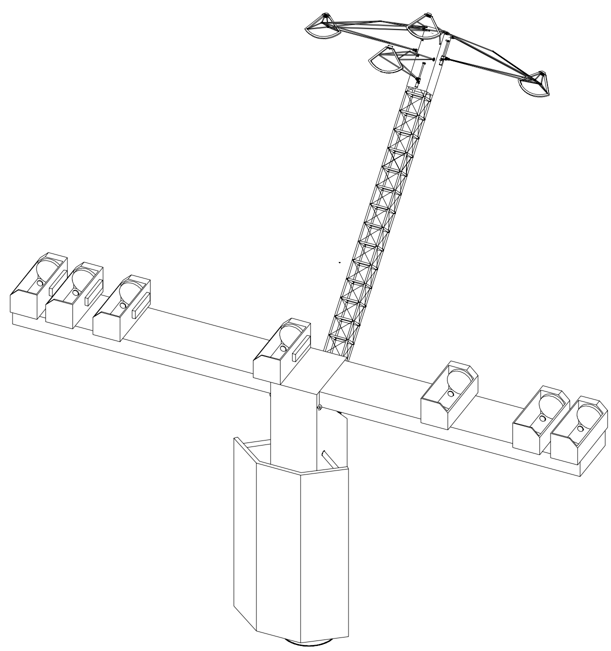

Figure 1. A line drawing of current reference design for the SIM Spacecraft. A series of seven siderostats arranged linearly on a 10 m boom allows SIM to concurrently form three pairwise-combination interferometric baselines. Light collected by the siderostats is relayed down into the optical bay. The optical bay houses delay lines, beam combiners, metrology components, solar panels, control electronics, and ancillary spacecraft functions. An external metrology truss supports beam launcher assemblies arranged in a tetrahedral geometry. The metrology beams continuously interrogate optical fiducials on the surfaces of the siderostats, and monitor the relative 3-space geometry of the three interferometer baselines.

2. SIM ASTROMETRIC MODEL

The astrometric model for SIM is quite different than the Hipparcos mission, and deserves a bit of explana-

Instrument	
Baseline	10 m
Wavelength Range	400 – 1000 nm
# Siderostats	7
Aperture Diameter	30 cm
Astrometric FOR	15° diameter circular
Imaging FOV	2.4 × 0.4 arcsec
Detector	Si CCD and APD
Sun Exclusion Angle	45°
Mission/Flight System	
Orbit	900 km Sun-Synch
Orbit Period	103 min
Launch Vehicle	Delta-II 7920
Mass	1800 kg (79% Margin)
Power	1030 W (63% Margin)
Lifetime	5 yrs
Science Performance	
Astrometry (wide-angle)	4 μas/20 mag/14 hrs
Astrometry (narrow-angle)	1 μas/15 mag/3 hrs
Imaging Resolution	10 mas @ 500 nm
Imaging Sensitivity	20 mag/pixel in 1 hr
Nulling	10^{-4}

Table 1. Synoptic view of the SIM instrument, mission, and science performance.

tion. SIM traces its astrometric heritage to the wide-angle astrometric experiments conducted in the late 1980s with the Mark-III interferometer at Mt. Wilson (Shao 1990). In SIM astrometry, objects are measured serially with a single interferometric baseline **B**, and a sequence of object measurements are used to estimate the baseline geometry and object geometry projected along the baseline vector. At each observation the instrument is held (approximately) inertially stable while the starlight is collected and metrology measurements are made. The observable is the internal delay d required to equilibrate the starlight pathlengths in the two interferometer arms as measured by an internal laser metrology system. This delay value is given by the interferometer astrometric equation:

$$d = \hat{\mathbf{s}} \cdot \mathbf{B} + C + \epsilon \tag{1}$$

where $\hat{\mathbf{s}}$ is the unit 3-vector to the observed object, C is a so-called *constant* or bias term that represents possible optical path differences between the light collected from the target object and the internal metrology, and ϵ is a noise term resulting from the finite accuracy of the internal metrology measurement. For astrometric measurements at the 4 microarcsec (2×10^{-11} rad) level we must measure this internal delay to approximately 200 picometers (for a 10 m baseline).

Herein we make an important assumption: that it is *very* difficult to cross-calibrate the constant terms between the multiple interferometers on the SIM spacecraft. Thus to minimize systematic errors *the measured delays used in astrometric reductions are taken from just one single interferometer.* In this model SIM *does not* directly measure the relative angle between objects in the sky, instead it measures delays to multiple objects that are inter-related by our knowledge of the interferometer baseline vector and its evolution in time. It is precisely this time-evolution knowledge of the baseline attitude that the ancillary guide interferometers are used to measure (length and relative geometry evolution being monitored by the external metrology system). Given the nature of Equation 1, to exploit the precise delay measurements SIM makes we must eventually know the baseline vector and its evolution to an accuracy commensurate with our delay measurement precision (i.e. hundreds of picometers). The baseline vector attitude and length are not *a priori* known to sufficient precision by any direct measurement – instead they are estimated as part of the astrometric reduction process.

3. REFERENCE GRID AND MEASUREMENT MODES

Science measurements with SIM are made by observing science targets in conjunction with objects in a global reference grid. Contemporaneous observations of reference grid objects serve as the astrometric calibration of the instrument at a particular epoch, as well as the global truss work by which science objects separated by angles larger than the 15° Field of Regard (FOR) are compared. By our current conception the reference grid is established and maintained by separate, periodic measurement campaigns throughout the SIM mission lifetime. Between these reference grid campaigns the SIM instrument is free to perform science operations – both astrometry and imaging. Unlike the Hipparcos instrument and implied great circle sky coverage model, the SIM instrument is free to pursue different science objectives (astrometric and imaging) in different operational modes. To support the mission goals of 4 microarcsec (μas) global astrometry, the reference grid solution must be accurate at the 2 – 3 μas level over the life of the mission.

3.1. Grid Campaign Sky Coverage

Because of the large field of regard transverse to the baseline direction and stop-stare astrometric measurement mode, SIM is poorly suited to perform the great circle scanning and measurement reduction employed by the Hipparcos mission. Instead, at present we envision a systematic interlaced brickwork-like pattern of sky coverage with discrete pointings that we have termed *tiles*. For reference grid observations, each tile consists of a sequence of delay measurements for available grid constituents. 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 minus the Sun exclusion zone) is traversed twice in two quasi-orthogonal baseline orientations to provide isotropic measurement errors. The scan pattern 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 then final circle of tiles is again at the periphery of the Sun exclusion region. We refer to the entire process as the *Orange Peel* scan model, and estimate that SIM can complete an Orange Peel sky coverage in 20 – 30 days. (To aid in visualization, MPEG computer animation visualizations of the SIM Orange Peel scan model can be found at http://sim.jpl.nasa.gov/sim). At present we estimate that roughly four of these Orange Peel campaigns will be required per year to achieve suitable reference grid performance, requiring roughly a third of mission observing time.

3.2. Grid Size and Constituency

At a minimum four reference grid objects are required to support interferometer calibration at a particular instrument pointing. This requirement, along with the 15° astrometric FOR sets a lower limit of approximately 1000 objects in the global reference grid. However, as we anticipate some attrition among objects deemed suitable for the reference grid, prudence dictates we carry additional objects to avoid locally insufficient grid coverage. Consequently at present we are assuming a reference grid of approximately 3000 objects.

The chief constituents of the reference grid will be relatively bright stars ($V \sim 6 - 12$) whose observation time is setup and metrology-integration dominated. One strategy is to choose classes of objects that would be relatively immune to anticipated sources of microarcsec astrometric jitter, say early-type main sequence stars at hundreds of parsecs. However, it will be difficult to suppress sources of astrometric jitter completely, so some argue that reference grid objects should be chosen from among an unbiased sample of object classes. At present the correct strategy is unclear, and this question will be investigated in ground-based studies until SIM launch (see Section 3.5.).

Among the reference objects SIM will observe approximately 100 extra-galactic objects (nominally QSOs) to establish a quasi-inertial anchor for the reference grid. Some fraction of the observed QSOs will be radio-loud so as to facilitate a SIM optical/VLBI radio frame tie.

3.3. Grid Astrometric Reductions

As SIM does not cover the sky by great circle scanning, the grid astrometric reduction is made by a direct sphere solution strategy. Following the model of Hipparcos, an *a priori* 4π model of object position, motion, and parallax combined with instrument models (baseline lengths, attitudes, bias terms) can be fit to the measurement set from the grid observations. Following Loiseau & Malbet (Loiseau 1996), we have created simulation programs to numerically study the performance of SIM grid reductions parametrically with instrument performance, mission design, and astrophysical parameters through Monte Carlo techniques (Boden 1997). Figure 2 illustrates a study of reference grid reduction performance as a function of astrometric FOR, and led to the current SIM reference design value of 15°.

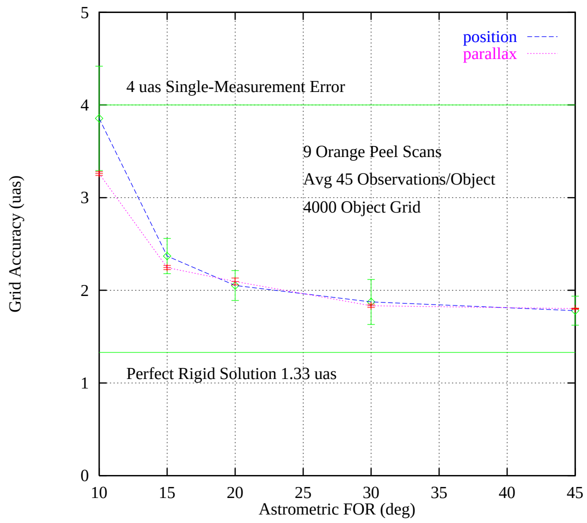

Figure 2. Numerical results on SIM astrometric grid performance as a function of astrometric Field of Regard (FOR). The conditions of the experiment were 4 μas input delay errors on a reference grid of 4000 objects observed by the Orange Peel model for two years. Clearly the rigidity of the reductions improve with larger (FOR), a result which is well known in great circle reductions from Hipparcos and Romer/GAIA analyses (e.g. Makarov et al. 1994).

3.4. Metrology Performance Implications of Grid Reduction

Mentioned above, SIM includes an integrated external and internal metrology system. Among its principle functions is monitoring the time-evolution of the interferometer baseline geometry. Because SIM requires a significant amount of time (e.g. 3 weeks) to cover the sky so that a closure condition invoked, it is this metrology system that monitors the systematic variations sure to be present. In the SIM concept, so long as the metrology system is a stable and faithful measure of the differential changes in the interferometer geometry, delay measurements (corrected for time-evolution) taken at different times can be directly combined. However, discontinuities or systematic changes in metrology coverage break this condition and require additional interferometer model parameters (chiefly baseline length or scale). While the design goal in SIM is to have long-term metrology stability, our numerical simulations suggest that reference grid reductions are reasonably robust against metrology discontinuities. Figure 3 shows a specific comparison of parallax error in reductions of two years of grid observations with no metrology breaks, and a break between each successive peel. (Other conditions for this test were similar to the FOR study depicted in Figure 2: 4 μas delay measurements, 4000 objects, 15° FOR). The reduction with metrology breaks exhibits only a 5 per cent increase in rms parallax error over the unbroken metrology reduction; increases in position and proper motion error were similarly modest. While this issue is still under intensive study, initial indications of grid reductions performance with metrology faults are quite encouraging.

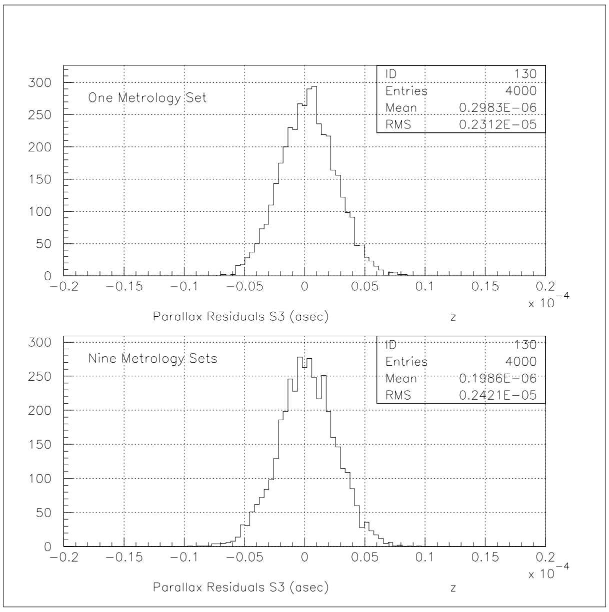

Figure 3. Numerical results on SIM Astrometric Grid Performance as a function of metrology continuity. Here we compare the observed distribution of parallax error for a reduced data set with complete metrology continuity, and a data set with metrology breaks between successive peel scans. The conditions of the experiment were 4 μas input delay errors on a reference grid of 4000 objects observed by the Orange Peel model for two years with 15° FOR. Initial indications are the reductions are surprisingly resilient to metrology faults. Introducing the metrology faults causes a only 5 per cent increase in the observed rms parallax error; results in position and proper motion error are similar.

3.5. Astrometric Jitter on Reference Grid Objects

Astrometric reductions nominally assume astrometrically ideal motions for the objects – simple proper motion and parallax (e.g. Kovalevsky et al. 1992). But with the advent of microarcsec-class astrometric techniques comes attendant difficulties with complex object motions that we refer to as *astrometric jitter*. While we essentially have no *a priori* empirical knowledge of astrometric stability at the microarcsec level, we can enumerate a number of known causes of astrometric jitter that will be a present at the microarcsec level:

1. Starspots
2. Binary (multiplicity) (Weilen 1997)
3. Planetary Companions (Butler et al. 1997)
4. Gravitational Microlensing (Høg et al. 1995)
5. Relativistic Outflows in QSOs

Conventional wisdom would dictate that reference grid objects should be selected to mitigate the possible effects of this astrometric jitter. (Although it is unclear the extent to which such astrometric jitter in fact degrades the performance of the reference grid reductions (Perryman 1997); this issue is currently under study.) In terms of selecting suitable candidates for the SIM reference grid, we envision an active ground-based observing program to detect the presence of unknown binary companions. The most efficient scheme for this search would seem to be a differential phase-referenced detection technique using the planned Keck Interferometer (Kulkarni et al. 1996; Peterson 1997b). Differential astrometric searches with the Palomar Testbed Interferometer (Colavita et al. 1994) and through radial velocity techniques are also possible, but take significantly longer.

4. NON-GRID ASTROMETRIC OBSERVATIONS WITH SIM

Wide-Angle Astrometry: The grid observation tile concept serves as the prototype of all global astrometric observations with SIM: some sequence of objects are 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 observe 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 an 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. The accuracy goals for SIM global astrometry are 4 μas in position, proper motion, and parallax, but the inherent flexibility of SIM's astrometric mode allows individual programs requiring varying levels of astrometric performance to be tailored to maximize observing efficiency (up to the accuracy limits of the global reference grid).

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°) fields at an accuracy of 1 μas. SIM's differential mode is suitable for science programs where global references are not required, but the highest possible differential performance is desirable. The improvement in astrometric performance follows from the expectation that the dominant systematic errors in SIM astrometry will be field-dependent errors in the metrology fiducials. In the prototypical narrow-angle program SIM would again observe available global reference grid objects to estimate interferometer attitude, length, and bias. But in narrow-angle mode an ancillary set of reference objects near the science target and (possibly) separate from the global reference grid are also observed in conjunction with the science target(s). The global reference grid observations constrain interferometer parameters such as scale, but the astrometry of the narrow-angle references and science target(s) are estimated independently through traditional differential astrometry techniques. (Residual scale and bias term errors due to finite accuracy of the wide-angle references is reduced by the ratio of the wide and narrow-angle field sizes).

5. SUMMARY

SIM holds the promise of making a wealth of exciting astrophysical discoveries in the next decade. As presently envisioned, global astrometry with SIM is underpinned by a global reference grid that is periodically observed in dedicated campaigns. The instrument design, specifically the integrated metrology system, provides the necessary stability to accomplish global astrometry with small levels of systematic error. Narrow-angle astrometry is similarly supported by the reference grid, but only for scale and bias term solution. To support the global astrometry objectives, this reference grid must be accurate at the $2-3$ μas level. We are currently studying the performance of the reference grid as a function of instrument, mission, and astrophysical parameters, and initiating ground-based programs to study sources of astrophysical jitter.

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REFERENCES

Boden, A. 1997, JPL/SIM Internal Memorandum ABODE9702031 (http://sim.jpl.nasa.gov/sim)

Butler, P. et al 1997, ApJ 474, L115

Colavita, M.M. et al., 1994, Proc SPIE 2200, 89

Høg, E., Novikov, I.D., and Polnarev, A.G. 1995, A&A, 294, 287

Kovalevsky, J. et al. (the FAST Consortium) 1992, A&A 258, 7; and Lindgren, L. et al. (the NDAC Consortium) 1992, A&A 258, 18

Kulkarni, S. et al. 1996, BAAS, 189, #32.02

Loiseau, S. & Malbet, F. 1996, A&AS, 116, 373

Makarov, V.V., Høg, E., & Lindegren, L., 1994, preprint

Perryman, M. 1997, private communication

Peterson, D., et al. 1996, Final Report of the Space Interferometry Science Working Group

Peterson, D., & Shao, M. 1997a, these proceedings

Peterson, D. 1997, private communication

Shao, M. et al., 1990, AJ, 100, 1701;
Elias, N. et al., 1993, BAAS, 183, #73.09

Shao, M. et al., 1996, OSI NASA Science and Technical Review, JPL unpublished

Unwin, S., Boden, A., Shao, M., 1997, in 'STAIF-97' AIP Conf Proc 387, 63

Wielen, R. 1997, A&A in press