EXECUTIVE SUMMARY

This proposal is for the position of Instrument Scientist on the SIM Science Team. The PI of this proposal has 9 years of experience with SIM. He is the leader of SIM's major testbed, the Micro-Arcsecond Metrology Testbed (MAM). He is also an experienced astrometrist and is PI of an astrometric extra-solar planet survey at the Palomar 5-m telescope. He is experienced in high-precision metrology, interferometer systems, observational interferometry, and detector calibration.

We believe that it is of the utmost importance to report on some key, exciting science early in the mission. There are several motivations. First, and obviously, it is an insurance policy against a catastrophic mid-mission failure. Second, at the start of the mission, with several interferometers in the planning or implementation phase, NASA will be eager to issue press-releases describing scientific discoveries that capture the public's imagination. Third, early results and a technique that can duplicate those results throughout the mission will give the analysts important experience in the proper use and calibration of SIM.

The standard SIM observational scenario relies on the measurement of grid stars even for narrow angle observations. Unfortunately it takes years of observation to determine grid star positions to sufficient accuracy for the narrow angle measurements.

In this proposal, we present a technique for narrow angle astrometry that does not rely on the measurement of grid stars. We show through simulations that it can obtain *u*as accuracy and can detect extra-solar planets and other exciting objects with a few days of observation. It can be applied as early as during the first six months of in-orbit calibration (IOC). We call this technique Gridless Narrow Angle Astrometry, or GNAA.

We are proposing two independent science programs. The first utilizes GNAA to perform exciting early mission science: the unambiguous determination of exoplanet masses and the measurement of the mass of the black hole in Cyg X-1. The second utilizes the standard (and more observationally efficient) narrow- and wide-angle observing scenarios to measure the visual orbits of, and distances to, the optical counterparts of binary radio and x-ray systems.

Funding is provided for the PI, one co-I, and a post-doctoral fellow. The total cost for the 11-year proposal (FY'01-FY'11) is $1.1M. The funding covers research, data analysis, participation on the science team, and educational/public outreach participation.

1. Introduction

The Space Interferometry Mission (SIM) is capable of detecting and measuring the mass of terrestrial planets around stars other than our own. It can measure the mass of black holes and the visual orbits of radio and x-ray binary sources. There is no doubt that with the successful conclusion of the SIM mission, the Universe will contain many newly discovered planets and many breakthroughs in our understanding of complex astrophysical processes.

SIM achieves its high precision in the so-called "narrow-angle" regime. This is defined by a small (1^o) diameter field in which the position of a target star is measured with respect to a set of reference stars. The observation is performed in two parts: first, SIM observes a grid of stars that spans the full sky. After a few years, repeated observations of the grid allow one to determine the orientation of the interferometer baseline. Second, throughout the mission, SIM periodically observes in the narrow-angle mode. Every narrow-angle observation is linked to the grid to determine the precise attitude and length of the baseline.

The narrow angle process demands patience. It is not until five years after launch that SIM achieves its ultimate accuracy of 1 microarcsecond (*u*as). The accuracy is degraded by a factor of ~2 at mid-mission. As stated in the *Final Report of the Space Interferometry Mission Science Working Group*, "This being the case, much of the science will not be available until the end of the mission."

We believe that it is of the utmost importance to report on some key, exciting science early in the mission. There are several motivations. First, and obviously, it is an insurance policy against a catastrophic mid-mission failure. Second, at the start of the mission, with several interferometers in the planning or implementation phase [Terrestrial Planet Finder (TPF) and several others are now in the early concept stages], NASA will be eager to issue press-releases of scientific discoveries that capture the public's imagination. Third, early results and a technique that can duplicate those results throughout the mission will give the mission analysts important experience in the proper use and calibration of SIM.

In this proposal, we present a technique for narrow angle astrometry that does not rely on the measurement of grid stars. We show through simulations that it can obtain *u*as accuracy and can detect extra-solar planets with a few days of observation. It can be applied as early as during the first six months of in-orbit calibration (IOC). We call this technique Gridless Narrow Angle Astrometry, or GNAA.

We are proposing two independent science programs. The first utilizes GNAA to perform exciting early mission science. The second utilizes the standard (and more observationally efficient) narrow- and wide-angle observing scenarios to measure the visual orbits of, and distances to, the optical counterparts of binary radio and x-ray systems.

The science section of this proposal is organized as follows: In section 2, we define the early mission science goals. This is exciting science that will have an immediate and powerful impact – the precise measurement of extra-solar planet orbits and the measurement of the mass of a black hole. In section 3, we lay out the science goals for the available 1% of observing time for the remainder of the mission. The targets are relatively short-period binary systems exhibiting radio and radio/x-ray systems. They can be measured using the conventional approach, but are also suitable for GNAA if there is sufficient scientific motivation to devote observing time for quick results. We then describe in detail the GNAA technique in section 4, followed by a simulation in section 5.

The science sections are followed by the Instrument Scientist section. The PI of this proposal has 9 years of experience with SIM. In particular he is the leader of SIM's major testbed, the Micro-Arcsecond Metrology Testbed (MAM). He is also an experienced astrometrist and is PI of an astrometric extra-solar planet survey at the Palomar 5-m telescope. His experience and plans for his role as an instrument scientist are spelled out in the Instrument Scientist section.

2. Early Mission Science Goals

We have two early-mission science goals: the detection of extra-solar planets and the measurement of the mass of a black hole. By early-mission we refer to the initial 6-month period of In Orbit Checkout (IOC). According to the AO guidelines, observations performed during this period do not count against the available mission observing time. The procedures for IOC are in the early formulation stages. We believe that our GNAA technique will be both an invaluable checkout tool as well as a powerful scientific one during IOC.

2.1 Extra-Solar Planets

GNAA is good at measuring short-period signals. Several of the 36 known extra-solar planet candidates are ideal targets for the approach. SIM can determine the inclination and mass of the system, resolving the mass-ambiguity of RV measurements. SIM is the only instrument capable of confirming beyond any doubt that the RV signals are indeed consistent with planetary as opposed to brown-dwarf or larger masses.

Good candidates must have astrometric signatures >~4 *u*as, periods <<1 yr, and a surrounding reference frame containing at least 5 stars with V<10.5 within a 0.5 degree radius of the target. Table 1 lists 8 candidates. The list will grow as ongoing RV studies detect more planets. The lower signal limit may be reduced to ~1 uas by combining the astrometric data with RV data for improved SNR

Table I. Exoplanet candidates for Early Mission GNAA measurements

Star	GL 876	GL 86	HD168443	ρ CrB	HD195019	τ Boo	55 Cnc	HD192263
m2sini (Mj)	2.1	4	5.04	1.1	3.43	3.87	0.84	0.76
Spectrum	M4 V	K1 V	G5 V	G0 V	G3 IV	F6 V	G8 V	K2 V
m2sini (Ms)	0.3	0.8	0.9	1.05	1	1.2	0.9	0.77
P(days)	60.85	15.78	57.9	39.65	18.3	3.313	14.65	23.87
a(AU)	0.203	0.114	0.283	0.231	0.136	0.046	0.113	0.149
pi"(mas)	212.7	91.65	26.4	57.3	26.77	64.12	79.6	50.25
a"(mas)	43.2	10.5	7.5	13.3	3.65	3	9	7.5
a1"(mas)	0.301	0.052	0.042	0.014	0.013	0.011	0.008	0.007

2.2 Mass of Black Hole Cyg X-1

Cyg X-1 (HDE 226868) is a galactic, massive X-ray binary with an O type super-giant orbiting a black hole. The optical counterpart has a visual magnitude of 8.84 mag. Radial velocity measurements have determined its orbital period = 5.6 days (Gies, 1982). The absorption-line spectrum appears to be similar to comparable super-giants, but its atmosphere may be over-abundant in He and under-abundant in C. Many investigations have concentrated on its mass transfer process (Ninkov, 1987). This object is categorized as high mass X-ray binary whose primary is undergoing Roche lobe overflow. Spectroscopic analysis found He II λ4686 emission originating between the stars. It is noted that the Hα profiles appear to have two components, one moves with the primary's orbit, and another follows the quite different radial velocity curve of the He II λ4686 emission line. It is proposed that the second component is formed, like He II λ4686, in the focused wind flow between the stars.

However, the theory of mass exchange depends on observational results for this unique object. Polarimetric analysis favors the high-inclination results. The topographic reconstruction analysis of the Hα profile argues that the inclination of Cyg X-1 is low (about 28^o). (Sowers, 1998). Thus the super-giant never substantially occults the focused wind region. It can be expected that SIM will determine its inclination, and provide the solution for the arguments. It is interesting to determine the site of the focused wind emission, and whether the origin in the higher density flow is close to the super-giant. This will finally be possible by combining our orbital determination with spectroscopic measurements.

VLBI observations determined a trigonometric parallax of 0.73 +/- 0.30 mas (Lestrade, 1999). Hipparcos obtained a parallax of 0.58 +/- 1.01 mas (ESA, 1997). The large error ranges of those measurements must be significantly improved. In particular, there is no visual orbit available for this object. Our estimated semi-major axis is around 60 *u*as, which is well beyond the capabilities of any other ground- or space-based instrument. The visual orbit and precise parallax from SIM will lead to a good determination of the mass of the black hole.

3. Long Term Science

Our science program is not solely based on GNAA. The bulk of our proposed observations are made with the standard narrow- and wide-angle method because it is observationally more efficient (sect. 4.2) and because there is not necessarily a compelling reason to obtain early-mission results for these targets. However, the targets have short periods and are suitable for GNAA observations should the need/desire arise.

Radio stars are of particular interest in astrophysics and astrometry. Some radio stars are black hole binaries while others are RS CVn systems. Although many different techniques, including VLBI, X-ray observation, and spectroscopic analysis, have been used to study those radio stars, no visual orbit for any radio binary star has been published, and some fundamental physical issues are still unknown. Radio stars have been used to link the Hipparcos system to the extragalactic reference frame. Such link plays an important role to align the optical reference frame with the International Celestial Reference Frame (ICRF).

Table II: Initial List of Radio Sources

Star		Mag.	P.M. α	P.M.δ	d	P	a"_{phot}
			(mas/y)	(mas/y)	(pc)	(days)	uas
Cyg	X-1	8.8	-3.82	-7.62	1724	5.6	58
Algol		2.1	2.39	-1.44	35	2.86	132
σ2	CrB	5.2	-266.47	-86.88	23	1.14	193
LSI 61303		10.7	0.62	1.63	1150	26.5	50
V733	Tau	10.7	0.65	-24.89	148	51.1	190
V711	Tau	5.8	-32.98	-163.45	30	2.8	229
HR5110		5	84.7	-9.81	45	2.6	163
AR	Lac	6.1	-52.5	47.9	42	1.98	158
IM	Peg	5.9	-20.9	-27.6	97	24.7	392
UX	Ari	6.5	41.35	-104.29	51	6.4	125
V725	Tau	9.2	-5.08	-4.41	333	35	62
RS	CVn	8.1	-49.14	21.49	108	4.8	141
54	Cam	6.5	-38.28	-59.08	102	11.1	92
Z	Her	7.3	-23.63	74.25	98	3.99	88
SZ	Psc	7.4	18.11	26.06	88	3.97	81
HD224085		5.8	134.05	79.39	44	6.72	82

3.1 Nature of Radio/X-ray Binaries

Some radio systems also produce X-rays. An intriguing target is LSI 61303, which has been controversial since Hipparcos published a new parallax for this object.

LSI 61303 (HIP 12469) is one of a group of Be/X-ray sources. As generally assumed, Be/X-ray binary stars are relative bright x-ray sources containing neutron stars. The different X-ray properties of the systems are related to the orbital size of the neutron stars. Systems with small orbits have bright transients showing no quiescent emission as a consequence of centrifugal inhibition of accretion, while systems with wider orbits are persistent sources without large outbursts (Steele, 1998). LSI 61303 is a close system with a massive Be star. It has been identified as a non-thermal radio source, an X-ray source and a γ-ray emitter. Hipparcos data indicate a distance of 177 pc, which is 10 times closer than previously assumed value of ~2 kpc (Gregory, 1979). That difference in its distance has profound implication for modeling of this type of Be/X-ray sources. A new theory (Chevalier & Ilovaisky 1998) proposed that the unseen companion of LSI 61303 is a white dwarf, rather than a neutron star. The claimed scenario is that the primary is a compact object surrounded by an accretion disc of T_{eff} ~ 1500 K, which hides the central X-ray source. The accretion disc mimics the atmosphere of a Be star, resulting in the observed spectrum.

LSI 61303 was discovered through radio observations as a binary with P=26.5 days (Hutchings, 1984). Extensive spectroscopic observations conclude that the system is not an isolated Be star. It is a hydrogen-burning main-sequence star, not a post-AGB object. The reddening measurements to that object indicated that consistent E(B-V) ~ 0.70 from different methods is interstellar, not circumstellar in origin. Also, the object lies on the direction to the center of the Cas OB6 association. LSI 61303 most likely is a member of Cas OB6 association. Precise parallax of that star from SIM will be very useful to compare with an extinction corrected distance modulus of 11.9 to that association. The visual orbit and inclination of that system will provide the first good estimate of masses.

Similar Be/X-ray sources, such as V725 Tau, X Per, V801 Cen, HD 63666, HD 91188, et al., are also interesting in astrophysics, and need to be investigated by SIM. Here the narrow-angle mode of SIM is required to obtain precisions < 4 *u*as.

3.2 Origin of Radio Emissions

It is an important issue to find out where the radio emissions originates. As generally accepted, stellar radio emission comes from the whole corona. It has been discovered (Lestrade 1996) that two RS CVn type radio stars, UX Ari and σ^2 CrB, have a preferred site of radio emission which is the intra-system region. According to Lestrade, radio emission from these stars is due to the gyro-synchrotron process associated with large-scale magnetic field loops caused by high gravity in the intra-system region. Interactions in this region between loops attached to the surface of the two stellar components might produce reconnections required for electron acceleration. Now SIM can be used for direct comparisons between the optical and radio positions of these sources. We can compare a minute displacement of objects from SIM and VLBI observations. If the maximum displacement of the object from VLBI observations is close to the orbital diameter, radio emission must come from coronal activities.

3.3 Requested Observation Time

We have three categories of objects requiring different observation strategies:

1. High-priority, short-term measurements of planets and Cyg X-1 will be carried out during on-orbit checkout, i.e. the first 6 months of the mission. Each target will require 3 hours of observation (in the narrow angle mode) per 2-d data point. We anticipate up to 20 measurements per target. Because they are planned for IOC, these measurements do not count against the guideline mission time of 50 hr/yr.

2. For radio/X-ray binary stars the predicted semi-major photocentric axes are < 60 *u*as. We will use the standard narrow-angle mode to reach precisions of 1 *u*as. The parallax and proper motion are measured in follow-up wide-angle mode to a precision of 4 *u*as. Because these stars have periods < 30 days, we require a burst of observations over one period followed by 3 observations per year for 4 years. The total observing time for 10 measurements per orbit is 15 hours per source for the burst measurements and 3 hours per source over the remaining 4 years in wide-angle measurements. We anticipate a target list of 10 sources for a total of 180 hours.

3. For ordinary radio stars with semi-major axis of around 200 *u*as we will use the wide-angle mode. Each star will require 3 hours total for the mission, or a total of 90 hours for an anticipated target list of 30 sources.

4. Gridless Narrow Angle Astrometry (GNAA)

4.1 SIM's Baseline Approach

The process of performing narrow angle astrometry with SIM is in principle straightforward: SIM derives the baseline orientation, length, and delay constant by observing grid stars whose positions are know to a few microarcsec (*u*as). It then observes the target and nearby reference stars, ultimately computing the position of the target relative to the reference stars along the direction of the baseline. The baseline is then rotated (nominally within a few days) and the stars are re-observed to measure the position on the orthogonal axis.

Narrow angle accuracy is limited by the number of grid stars and their measured positional accuracy. Grid stars are spread over a 15-degree diameter 'tile' while the target and reference are confined to a 1-degree field at the center of the tile. To first order, for a given grid-star angular error *e*, the narrow angle error is ~ *e*/15, but this is subject to the intermediate step of baseline determination. Simulations show that on average 6 grid stars are required per tile if grid star errors of 4 *u*as r.m.s. are to contribute < 0.3 *u*as r.m.s. to the narrow angle solution.

The narrow angle measurement process does not achieve its full accuracy until the end of the mission because grid star positions, proper motions, and parallaxes are not known to their potential accuracy until then. A first grid star campaign is planned during the initial 6-month in-orbit checkout (IOC), but it will be ~ 1 year before an accurate parallax (~ 15 uas) is determined over a significant fraction of the sky. Thus the SIM science team does not plan to report accurate narrow angle results in a timely fashion, even for known short-period systems. The baseline narrow angle technique relies on the grid star campaign, evolving in accuracy over the 5-year mission life.

4.2 Efficiency

Narrow angle measurements are scheduled in an efficient manner to take advantage of grid star observations and other objects of interest within a tile. The narrow angle measurements are chopped into 1-minute long observations (30 seconds of integration, 30 seconds of slew and acquisition) with 10 observations per star per hour. Observation of a target and 2 reference stars would then require 30 minutes per hour. Observation of 6 guide stars before and after the narrow angle measurements would use another 12 minutes. In theory a full 2-d measurement could be completed in about ~1.5 hr.

Compared to the technique proposed below, the SIM narrow angle paradigm is more efficient. The new approach requires narrow angle observation of 4 reference and 1 target star, requiring the full hour (ten 1-minute long observations of 6 objects) to complete a cycle. Further, the new technique requires a minimum of 3 baseline pointings to make one 2-d measurement. After 3 hours, a narrow angle measurement is made on one interesting target. The advantage of course is that the measurement is good to ~ 1 *u*as after just 3 hours whereas the standard SIM approach requires >2 yr to make this claim.

4.3 A New Technique: Gridless Narrow Angle Astrometry (GNAA)

Narrow angle astrometry is nothing more than relative-angle astrometry. One measures the position of a target star with respect to a set of reference stars. In traditional narrow angle astrometry, a photographic plate or charge-coupled detector (CCD) stares at a field in successive observations. The field's reference stars are used to anchor a least-squares affine transformation that matches the scale, orientation, translation, and potentially higher order angular terms into a common reference frame. The transformation is then applied to the target star whose motion is observed relative to the reference frame.

The affine transformation absorbs several instrumental parameters that are of no consequence to observational accuracy. Changes in the telescope focal length are seen as plate-scale changes while telescope pointing errors are simply field translations, and detector rotation appears as field rotation. Without the global constraints of the grid stars, the absolute scale of measured parameters is lost, but the relative accuracy is still as good as the *a priori* knowledge of the field, *i.e.* 100 mas over 1 degree, or 3e-5. The minute absolute scale error will be dwarfed by other factors (e.g. shot and detector noise).

Gridless narrow angle astrometry (GNAA) with SIM is nothing more than the application of traditional narrow angle techniques to SIM's narrow angle optical path delay measurements. The technique, described in the following paragraphs, allows one to perform micro-arcsecond astrometry without solving for baseline length, precise baseline orientation, or the metrology constant term. In GNAA, a set of reference stars and a target star is observed at several baseline orientations. A linearized model is used to solve for reference star positions and baseline orientations. The target star position is determined using the estimated baseline orientations. Then the process is repeated at a later time and an affine transformation is applied to relate the reference target stars to a common reference frame.

As with narrow angle astrometry at a telescope, the affine transformation absorbs SIM instrumental parameters. To first order baseline length errors cause angular scale errors, baseline orientation errors cause rotational errors about the center of the reference frame, and the metrology constant term is a translation along the direction of the baseline. The affine transformation solves the scale, rotation, and translation of the observed reference frame without requiring the intermediate step of exact baseline determination. The absolute scale is lost, but it is estimated with a precision approximately given by the *a priori* scale knowledge of the field size.

The most significant advantage of GNAA is that high-accuracy narrow-angle measurements can be made early in the mission. As there is no reliance on highly accurate grid star positions, the technique can be applied during the 6-month in-orbit calibration (IOC) exercise. Thus SIM can obtain important scientific results soon after launch and throughout the early parts of the mission. Further, it is an ideal approach not only for early-mission science, but also for quick study and follow-up of compelling objects demanding immediate results. It is certain that some science will demand accurate results long before the 5 year mission is concluded!

The disadvantage of GNAA is that it is observationally inefficient. Unlike the grid-based narrow angle technique that allows sharing of a tile between narrow-angle and other targets, GNAA requires 3 dedicated hours of observation to produce a *u*as 2-d measurement of the target star. At least 4 reference stars and 3 baseline orientations are needed. This technique is clearly not the choice for producing the bulk of narrow-angle science observations once normal operations begin.

5. Simulation

5.1 Observations and Data Reduction

The GNAA technique has been demonstrated in a simulation described here. The simulation shows that given a set of stars *R* with only a coarse *a priori* knowledge of their positions, the baseline can be estimated with sufficient accuracy to determine the relative position and velocity (combined proper motion and parallax) of a target star with respect to a set *R'* of reference stars to ~1 uas precision for extended periods of time.

The set of stars *R* was chosen over a 1^o field-of-regard (FOR). The stars in *R* have an *a priori* positional knowledge of 100 mas. This could be easily obtained using ground based observations with a small aperture for stars not in the Hipparcos or Tycho catalogs. *R* is observed at 3 baseline orientations such that the baseline is rotated about the line of sight *s* in 60^o steps. The 60^o steps are assumed to be accurate to +/- $1^o.5$ as is the positioning of the baseline cant angle (out of the *s* x *B* plane). The baseline orientation is assumed to be known to 1 arcsec with information provided by star trackers, siderostat encoders, and coarse estimates of delay line position. Stars with V<10.5 are assumed so that the measured delay error is consistent with the SIM narrow angle error budget.

A crucial approximation in this study is the regularization of *B*. Imperfect spacecraft attitude control allows the baseline to drift by up to ~ 1 arcsec. Regularization describes the process of estimating the mean value of *B* using information from the guide interferometers and knowledge of the baseline geometry (guide baselines relative to the science baseline). The accuracy of this approximation is currently under study by the SIM modeling team. This approximation is always assumed in the standard narrow angle scenario as well.

Due to space limitations we will summarize the GNAA process but will not give detailed analysis. Starting with initial guesses at *R* and *B*, an estimate of both *R* and *B* is derived from a linearized model of the interferometer. The model does not include baseline length or the constant term. The updated baselines are then used to compute the relative positions of two independent reference stars *R'* and the target star *t* using the same linearized model.

The *R'* solutions are not yet accurate to microarcseconds. They contain large scale and rotation errors (~ 10 mas / 1 degree). To place all the stars in a common reference frame, a linear (scale, rotation, and translation) affine transformation is applied to the projected angular components s_{ei}' of *R'* such that $s_e = A(s_e')v$, where $A(s_e')$ is the affine transformation, s_e is the initial estimated position of the stars, and *v* contains the affine coefficients. *v* is determined from the pseudo-inverse of *A*. The accuracy of the projection is adequate because the stellar motions are small (described below). It is not necessary to use the true stellar positions in the affine transformation; since the goal is to put all subsequent observations into a common reference frame, the initial estimate s_e adequately serves that purpose. The transformation is then applied to the target star, $t_c = A(t')v$, where t' is the target position derived from the updated baselines B' and t_c is the measured position transformed into the common reference frame.

At the microarcsecond level, the reference frame is deforming itself; the reference and target stars are linearly moving in random directions due to proper motion, and they are moving in functionally predictable trajectories due to parallax. The amplitude of the parallax is not known. The simulation includes random (but linear in time) 10 mas/year motion per star per set of observations of *R* and *R*'. Curvature (in particular for the target star) of the motion due to parallax is not included because the science program searches for known short period signals that are easily decoupled from the annual parallax. The net result is that the target star motion is measured relative to reference frame motion without loss of information.

SIM's metrology will occasionally break. In the conventional (grid-based) narrow angle approach, it is allowed to break with every new field-of-regard because the grid stars allow recovery of the baseline and delay (constant term) parameters. With GNAA, the metrology is required to hold without breaks for 3 hours (3 baseline pointings). In the simulation the internal and external metrology is assumed to break with every set *B* of 3 baseline pointings. The 3-hour requirement should be easy to achieve with SIM because the grid campaign requires stable metrology for stretches of at least several days.

In summary the simulation includes the following effects:
1) Initial knowledge error of reference frame and target star positions = 100 mas (x and y)
2) Baseline positioning accuracy of +/- 1.5 degrees.
3) Knowledge of baseline pointing = 1 arcsec (around s and canting).
4) Accurate regularized baseline estimates.
5) Baseline absolute length knowledge = 10 microns.
6) Noise per delay measurement = 50 pm
7) Constant term knowledge error = 10 um rms (doable using ground calibration and on-board mechanical fiducials.)
8) Proper motion of stars = 10 mas/yr rms
9) Number of baseline orientations/2-D measurement: 3
10) Number of reference stars 5 (for baseline determination, 4 is minimum required). Two additional stars used as independent reference frame.
11) Constant term and baseline length error change every 3 hrs (after every 2-D narrow angle measurement).

5.2 Results

The simulation shows that GNAA can measure changes in the position of the target relative to the reference frame at the micro-arcsecond level. Even for extended periods in which the reference frame deforms by 10 mas, the noise level remains ~ 1 micro-arcsecond.

Fig. 1a shows the reference frame around a typical target 55 Cnc. All stars shown in the 1° field have V<=10.5. The figure indicates stars in *R* and *R'*. The orbital parameters for 55 CNC are given in Table I.

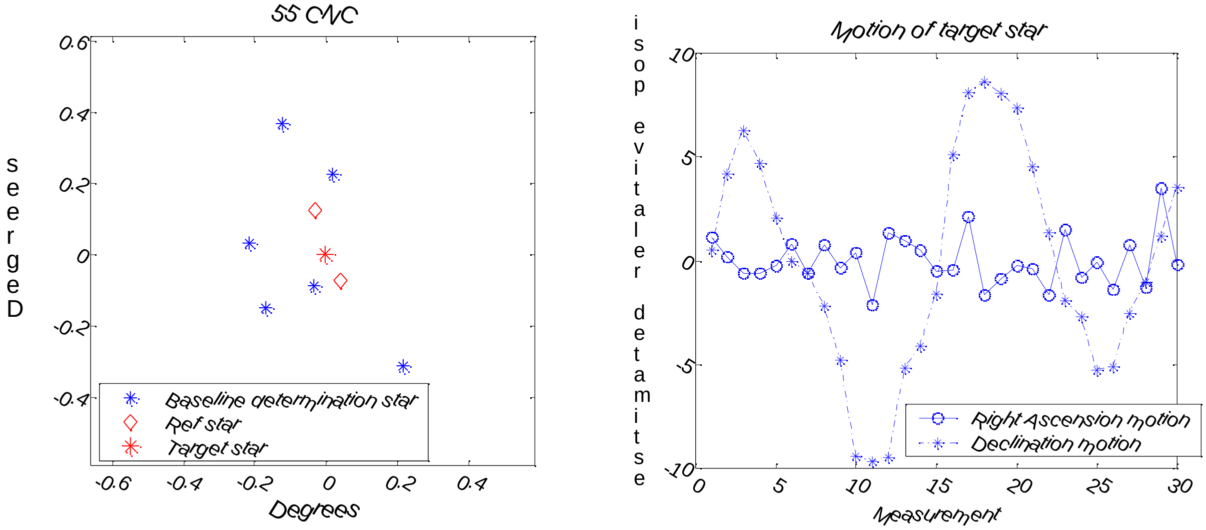

Fig. 1. a) is the selection of *R* (baseline determination stars) and *R'* (independent reference frame) surrounding the target. b) shows the result of 30 daily observations of 55 CNC. Each day, the baseline is oriented to 3 positions rotated 120° about the line of sight to the target. For demonstration purposes, the 8 uas signal is assumed to be a pure N-S sine wave. The R.A. axis thus indicates the noise level. Given the simulation parameters described above and this particular set of reference stars, the astrometric precision is 1.0 uas on each axis for each 3-baseline (3-hour long) observation. The reference frame has deformed by up to 300 mas due to proper motions of the reference stars. The relative proper motion of the target star has been fitted and removed.

The astrometric precision depends upon the distribution of stars in the reference set, the accuracy of the *a priori* positions of the reference frame and baseline, and the noise level per measurement. However, simulations show that by far the most sensitive parameter is the delay noise per measurement (50 pm rms). When this is set to 0 (no delay error), and all other parameters remain the same, the rms astrometric error is reduced to 0.23 uas. On the other hand, assuming perfect reference star knowledge and perfect baseline vector knowledge (but 50 pm rms noise) improves the precision from 1.0 to 0.95 uas. As the field size grows (in particular, the diameter of *R'*), sensitivity to baseline and reference star knowledge increases.

5.3 Future Work

The GNAA technique has been studied for this proposal but much work remains. The GNAA process ultimately needs to be described in the same analytical framework as the SIM grid and standard narrow angle reductions. Noise propagation and parametric sensitivities will be studied. In doing this, one hopes to describe an optimized process that makes more efficient use of grid stars and precious narrow angle observing time.

5.4 Acknowledgement

We would like to acknowledge the assistance of Dr. Mark Milman of JPL in the development of GNAA. He made many useful suggestions and greatly aided in our understanding of astrometry with SIM.

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EDUCATION AND PUBLIC OUTREACH

The PI and Co-I acknowledge the importance and priority of a strong education and public outreach (E/PO) program. We have included in our funding adequate resources to work closely with the E/PO mission scientist in the development of materials that will aid in the public understanding and interest in SIM. We will enthusiastically contribute to the enrichment of science and mathematics education, dissemination of printed and electronic materials, and the development of simulations and demonstrations of the SIM instrument and testbeds.

COST AND BUDGET

DESCRIPTION OF MISSION SCIENTIST ROLE AND RELEVANT EXPERIENCE

1. Relevant Experience

The PI of this proposal brings a wealth of relevant experience to the position of Instrument Scientist. He has worked for 9 years on the SIM project and is the leader of the Micro-arcsecond Metrology (MAM) testbed. He has worked in the field of interferometry for 15 years. He is also the PI of a narrow-angle high-precision observing program in its fourth year at the Palomar 200 inch telescope. He has experience in unique aspects of detector calibration and has a strong background in optics.

1.1. Micro-Arcsecond Metrology Testbed (MAM)

His most relevant experience is his leadership (both technical and managerial) of the MAM testbed. MAM is SIM's single-baseline high-precision (~ 200 picometer) system level testbed, incorporating both broadband artificial starlight and heterodyne laser metrology (Shaklan et al, 1998). The goals of MAM are twofold: first, develop the technology to demonstrate that SIM's interferometers can make astrometric measurements with microarcseconds precision. Second, perform a test that, with proper scaling, can be used to calibrate the flight instrument. The goals are extremely challenging for many of the same reasons that SIM is so challenging.

The MAM interferometer is a 1.5 m baseline instrument mounted on an optical bench inside a large vacuum chamber (fig. 1.1). Architecturally the interferometer looks like SIM: two siderostats follow a star and reflect the light into a delay line. The delay line equalizes the optical path which is measured both in dispersed white-light on a CCD detector and with a sub-aperture infrared metrology system.

The artificial starlight is formed by an inverse interferometer, referred to as IIPS (inverse-interferometer pseudo-star). IIPS generates two parallel, collimated, coherent beams of light emanating from a single-mode point source. IIPS articulates over a 15^{o} field-of-regard, necessitating many of the same coalignment and co-phasing systems, in addition to the same optical tolerances, as MAM.

MAM will develop the 'recipe' book for astrometric calibration at the micro-arcsecond level. Some examples of errors that require calibration are: corner-cube polarization and skin-depth effects which make the vertex (and therefore the baseline) appear to move as the incident angle of the beam is changed; delay-line non-axial motion that causes the beam to walk across the optics, leading to optical path errors; and similarly, periscope modes of the siderostat/fast-steering mirror pair that also lead to beam walk; sub-pixel gradients in the CCD that affect the mean wavelength of the light in the dispersed fringe; diffraction differences between the uniform 5 cm diameter starlight beam and the Gaussian-profile 1 cm diameter metrology beam; metrology cyclic errors caused by leakage in the polarizing optics; changing thermal gradients across the optics,… and the list goes on.

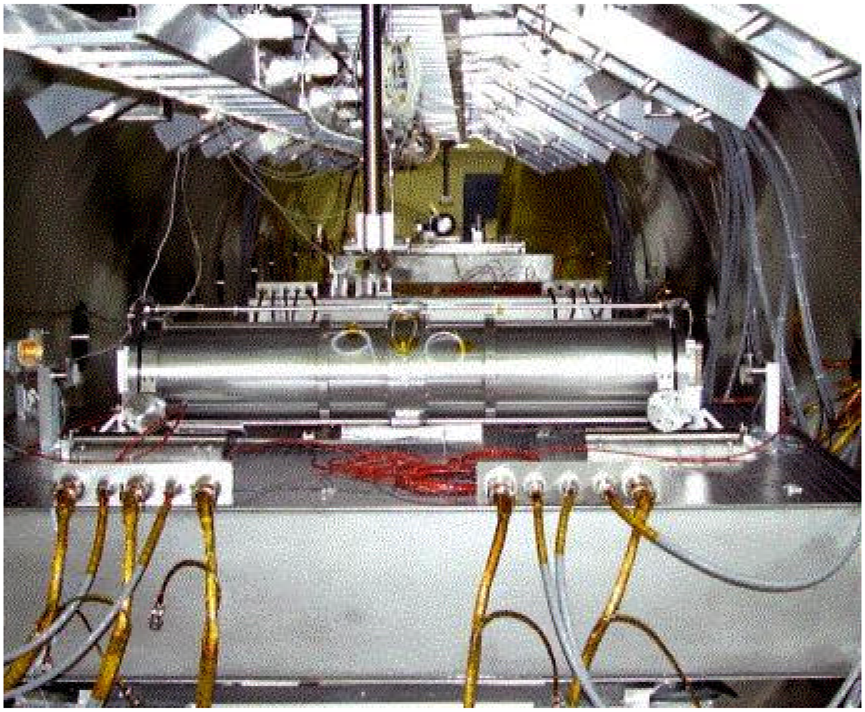

Figure 1.1. View inside the Micro-arcsecond Metrology (MAM) vacuum tank. The 40-foot long tank houses 3 optical benches. The dual delay line (large cylinder) and several beam-combiner optics are visible in the foreground. Two optical benches are visible in the background. These are to be used for the 2-D metrology experiment in conjunction with the MAM experiment.

MAM is already impacting the design of SIM. In designing the MAM automated alignment procedure, it was discovered that additional degrees of freedom (compared to the existing SIM design) had to be controlled in the beam combiner to allow simultaneous measurement of both guide spots and fringe light. This has led to a split of the SIM guide and fringe detectors.

The combination of MAM and IIPS is the model for the SIM astrometric flight test. A 10 m version of the IIPS will be built for the flight test. It will be placed in a large vacuum chamber with SIM and will direct collimated beams into one of the SIM interferometers. Thus, the lessons learned on MAM will directly impact the procedures and techniques applied to the calibration of SIM.

1.2. Other SIM Activities

The PI has participated in the development and planning of SIM since 1991. When MAM began, he served as the metrology architect for the mission, leading the development of numerous metrology components. He served as the lead optical engineer for the Micro-Precision Interferometer (MPI), a dynamics testbed consisting of an interferometer mounted on a floating truss. He led the early studies of SIM imaging performance and has participated in many other SIM trade studies.

He was the cognizant engineer for the SIM brassboard astrometric beam combiner. Brassboard hardware is designed to withstand the vibrations and acoustic noise of the launch, to operate in vacuum, and to have similar form, fit, and function as the flight hardware. In designing the brassboard astrometric beam combiner hardware, new athermalized, low-stress, adjustable, and stable optical mounts were developed. He was responsible for the development and implementation of the assembly, alignment, and all testing functions. The beam combiner has been used in the real-time software development support configuration and is being considered as the model for the Separated Spacecraft interferometer (ST-3 mission).

He also invented an alternative interferometer architecture, known as "Son of SIM" which was selected as the mission architecture for 18 months before the project decided to revert to the present design in mid-1999. The SIM/Son-of-SIM trade study revealed numerous calibration issues and led to a greatly improved understanding of both architectures as well as the supporting testbed programs.

1.3. Interferometry

The PI has 15 years of experience in the field of interferometry. He was the first to demonstrate imaging with a multi-element interferometer whose apertures were interconnected using single-mode fiber optics (Shaklan 1990). He invented the technique of visibility calibration and seeing desensitization using single-mode fibers (Shaklan, Shao, and Colavita, 1991); the technique is now in use at the Palomar Testbed Interferometer and at the IOTA array on Mt. Hopkins. He also maintains an interest in the application of adaptive optics to interferometry (Buscher & Shaklan, 1994).

1.4. Astrometry

The PI has been working in the field of astrometry since 1991 when he joined of the Astrometric Imaging Telescope (AIT) team. He simulated the telescope performance accounting for the optical design, optical surface errors, diffraction effects, and detector non-uniformities in showing that AIT could achieve a precision of 10 uas (Shaklan & Pravdo, 1993).

The AIT work led to the invention of a technique for measuring the relative position of CCD pixels with an accuracy of 1/500 pixel(Shaklan, Sharman, and Pravdo, 1995). This work discovered a periodic 1 mas astrometric error in the WF/PC II CCDs.

Another outgrowth of the AIT work was the Stellar Planet Survey (STEPS), a large-format CCD-based observing program at the Palomar 5-m telescope. The narrow-angle astrometry project, now entering its fourth year, is surveying nearby M-dwarf stars in an astrometric search for Jupiter-mass planets. Early results demonstrated better than 200 uas precision within a single night (Pravdo & Shaklan, 1996). The project is now attempting to achieve this result over the long term. The PI is a co-PI on STEPS and is responsible for the observations, system and optical design, and end-to-end data analysis including the bulk of the analysis software. It is precisely the experience with STEPS that led to the application of traditional narrow-angle techniques for SIM presented in this proposal.

2. Contributions

As an instrument scientist, the PI will make major contributions to SIM in three areas: 1) develop optimized observing strategies to mitigate systematic errors; 2) advise the science team on all matters related to picometer measurements, including systematic errors in both starlight and metrology systems, calibrations, performance expectations, and detector issues; and 3) invent and study on-orbit calibration procedures and alternative observing techniques.

2.1 Optimized Observing Strategies

SIM achieves an astrometric accuracy of 1 uas by measuring optical delays to an accuracy of 50 pm. Such extreme accuracy is realized in the presence of large systematic errors that require not only calibration, but also a methodical observing strategy designed to mitigate their effects. The systematic errors appear in three flavors: field-dependent, temperature-dependent, and instrument engineering-dependent. Optimal observing strategies can improve performance in the first two categories, as described below. Calibration of terms that are strictly dependent on instrument engineering must be addressed by ancillary means. In this section we review the systematic errors and describe how the observing program can best be structured to limit them.

Field Dependent Errors

Field-dependent systematic errors arise when the science interferometer is pointed from target-to-target. Two major components are moved to achieve this: the siderostat and the delay line. The siderostat serves two purposes; it directs the starlight into the instrument and it supports a cube corner that retro-reflects both internal and external metrology beams. When the siderostat tilts, the projected entrance pupil becomes more or less elliptical, thereby illuminating different parts of the imperfect optical surface. The surface imperfections change the average pathlength of the beam by 10s of picometers (depending on the optical quality). Tilting of the siderostat also tilts the cube corner. This changes the illumination pattern and modifies the polarization of the metrology beam. Both of these effects introduce optical path errors in the metrology beam. Further, the cube corner vertex sits a finite distance (< 1 micron) above the siderostat; as the siderostat is rotated, the projected separation between the vertex and siderostat surface changes, effectively introducing a variable optical delay between starlight and metrology.

The delay line slews to equalize the optical path between the arms of the interferometer. It compensates for up to 2.6 m of delay across the 15 degree field-of-regard. Two important systematic errors, diffraction and beam walk, arise from this. Diffraction introduces wavefront curvatures that cause the measured optical delay of the metrology and starlight beams to differ from the geometrical (axial) delay. The effects are large: 100-200 pm differences arise between starlight and metrology over the field of regard. They are also quasi-periodic with a period of ~ 10 cm, and are sensitive to the size of the down-stream optics and the field stop. Any motion of the delay line transverse to the starlight beam (as occurs when the delay line rails are misaligned or warped) gives rise to the beam walk across the downstream optics. It can be shown that on a high quality (lambda/100) optic the optical path error related to beamwalk is ~ 1-2 pm per micron of transverse motion.

What can be done to reduce field-dependent errors? Obviously, the best strategy is to reduce the size of the field. Most of the errors just described scale linearly with the field. Thus by observing a set of stars over a 1 deg field-of regard the effects are immediately reduced by a factor of 15 compared to the wide-angle case. One important term that is not linear in field angle is diffraction which has a periodicity of ~ 10 cm. By reducing the field of regard to 1 deg (17 cm delay) this effect still requires substantial calibration. This term drives the desired field of regard to ~ 0.25 deg so that a simple quadratic fit can be used to describe the systematic behavior. While stellar population densities may make this field impractical in most cases, it may be desirable to bias the program towards the smallest field possible, weighing the likely systematic effects against the random detection (shot and read) noise level.

It is worth noting that independent of the field-dependent errors, the astrometric model inversion (solving for exact star and baseline parameters) performs better as the field size is reduced. This is because the equation d=b * sin(theta), where theta is the angle between the star and baseline, becomes more linear as the field size is reduced. Finding target stars with nearby reference stars is a win-win situation for both systematic error rejection and model-fitting purposes.

Temperature Dependent Errors

Over time, temperature drifts cause the spacecraft to deform, optical surfaces to warp, and metrology component pathlengths to change. A large athermalized spacecraft structure can be expected to bend by 10-100 microns over several hours, depending on external factors (e.g. changing projection of the earth and sun) and internal factors (e.g. thermal control system and overall heat load). When the spacecraft bends, the starlight and metrology beams, which are forced to be parallel at the beam combiner to maintain fringe visibility, walk across the optical train. Beam walk errors appear, as in the previous description. Thermal drifts in the optics are also an important consideration, primarily at the siderostat and beam compressor since they are the most susceptible because they are directly exposed to space. Time-dependent warping of the optics introduces relative delays between starlight and metrology. The other critical area that is sensitive to temperature drifts is the metrology system, in particular the beam launchers. The launchers are complex optical devices designed to be athermalized with respect to bulk temperature changes but not with respect to thermal gradients. Changes in the gradient across a launcher introduce tens of pm/mK. Since the beam launchers necessarily have openings that allow the metrology beams to see the optics and spacecraft, controlling thermal gradients to sub-milliKelvin levels is extremely challenging.

The primary weapon against thermal drifts is chopping of the observations. The time-constants for the sensitive components range from ~ 30 minutes to several hours. Observing the target star and reference stars within a 5-10 minute window then repeating the observations until the desired SNR is reached can in large part mitigate thermal drifts. Each target/reference cycle will shift and potentially scale with respect to the others. This is inconsequential for narrow-angle astrometry (with an adequate number of reference stars). Chopping with a 5-10 minute cycle will reduce thermal-dependent errors to well below 50 pm.

A complementary strategy is to schedule the observations so that the most demanding ones are the last ones for a given tile. For example, given a one-hour observation on a tile in which grid, other wide angle, and exoplanet narrow-angle observations are scheduled, the narrow-angle work should be last. This allows maximum time for decay of the thermal gradients. It might also be desirable to perform a short calibration observation on 2-3 bright stars just before and after the narrow-angle work as a means of estimating the linear drift terms.

Instrument Engineering Dependent Errors

There are many errors in SIM that are neither field- nor time-independent. There are two categories; pointing errors and spacecraft coordinate errors. Pointing errors are misalignments between the two starlight arms, and between starlight and metrology. They arise from erroneous auxiliary sensors such as guide star cameras, beam shear sensors, and metrology/starlight coalignment sensors. Starlight misalignments are another source of beam walk, while metrology misalignment (with respect to starlight) is a geometric error that is proportional to the cosine of the angle between the starlight and metrology beams. Except for a second-order dependence on the color of the science target, these systematic effects are independent of the length and sequence of the observations. One can reasonably argue that the sensors will have a more random behavior if the observations are chopped, e.g. some of the sensor behavior may have thermal origins. So our chopping strategy will help, but it is not clear how much.

Spacecraft coordinate errors are those arising from both the absolute and relative external metrology measurements. Metrology errors lead to both an overall baseline length error (to which narrow-angle inversion models are sensitive), and to errors in baseline regularization. This refers to the process of using the guide interferometers and auxiliary sensors to estimate the mean baseline position during an observation in which the baseline is drifting. Chopping with a 5-10 minute cycle does not help here because the baseline drift has a time constant of ~ 1 minute.

2.2 Picometer Guru

As noted above, the PI has substantial experience working on the picometer systems testbed (MAM). The MAM testbed is not just a breadboard version of a SIM baseline. It is the prototype microarcsecond flight-test demonstration, and it will evolve into a picometer brassboard test facility as flight-like hardware becomes available. As a system testbed, MAM is having a major impact on the development of not only the metrology and starlight detection systems, but also a suite of auxiliary sensors and procedures that control or eliminate systematic errors. As the lead advisor to the science team on picometer issues, a thorough understanding of these interdependent sensors and procedures is crucial. Several examples are given here:

Shear sensors: As noted above, the “walking” of starlight and metrology beams on the optics is an important contributor to the error budget. Beam walk occurs not only in SIM but in the pseudo-star as well. Controlling the relative beam walk between the pseudostar and SIM (or MAM) requires the use of a shear sensor accurate to a few microns. The shear sensor’s intrinsic problems are the ability to function over a range of distances (to accommodate delay line motion), sensitivity to both the starlight and metrology light that are ever-present in the system, and making its own source invisible to the CCD and metrology detectors.

Metrology/Starlight Alignment Unit: It is imperative that the metrology and starlight beams be parallel to one another and parallel to the motion of the delay line. The alignment unit (ALU) performs this job by detecting the metrology beam and starlight beams on separate quadrant photodiodes whose relative positions are calibrated. The ALU sits behind a beamsplitter that reflects the light into the delay line and beam combiner. Motion of the beamsplitter can affect the light in the beam combiner unbeknownst to the ALU. A complete understanding of the ALU alignment procedure and telltale signatures on the guide and fringe detectors is required to maintain alignments throughout. The PI will have significant experience with this before SIM is launched.

Detector issues: CCD and other array detectors suffer from non-uniform response across a pixel and from pixel-to-pixel. When light is dispersed across the array, each pixel has an effective wavelength that depends on the intensity gradient multiplied by the response gradient (and potentially higher order terms as well when there are deep spectral features). As SIM moves from star-to-star, and over time as the CCD response evolves, the effective dispersion changes and must be recalibrated. This affects the performance of the picometer white-light fringe detection algorithm that depends on the spectral binning, on-chip dithering, and the number of optical path steps. A detailed calibration procedure is required for the various conditions.

The job of the “picometer guru” will be to understand and explain these types of calibration issues with respect to both the wide- and narrow-angle observation scenarios.

2.3 On-Orbit calibration Procedures

Presently, there does not exist a set of on-orbit calibration procedures that cover all the known systematic errors in SIM. Not only is it critical to invent these procedures before launch, it is also crucial that the proposed calibrations be proven in the testbeds and in the pre-launch flight-system astrometric test.

Several on-orbit calibrations are being considered. These calibrate spacecraft roll (about the baseline vector), diffraction errors (see sect 2.1), beam shear, and dispersion. However, none of the calibrations have yet been proven to work and it is known that at least the diffraction error calibration does not truly duplicate the conditions of the starlight because it is based on retro-reflected white-light that sees the field stop (and all intermediate optics) twice.

We reemphasize that calibration is crucial to the success of SIM. The field-dependent effects mentioned in sects. 1.2 and 2.1 are typically between 100 and 100,000 pm. For the most part they are low-order and static across the field-of-regard. The goal is to calibrate them to ~ 10 – 100 pm.

The GNAA approach when applied multiple times to the same field of stars is a good example of on-orbit calibration. We showed above that GNAA requires 3 baseline pointings and 5 reference stars. By observing the same field with redundant baseline pointings (e.g. 6 pointings in various orientations), one can perform parametric fits to diffraction and beam walk errors with a 2-d complexity that depends on the number of pointings and the number of reference stars. The accuracy of the fits will be between 1-10 uas depending on the size of the field. GNAA allows calibration at the micro-arcsecond level at any point during the mission.

2.4 Co-I Contributions

The Co-I Xiaopei Pan brings a wealth of interferometry experience to the table. Pan has 13 years of experience in optical/IR long baseline interferometry. He created a data analysis package for the

Mark III Stellar Interferometer on the Mt. Wilson, CA, and was actively involved in the solution to engineering problems. He published the first visual orbit with sub-milliarcsecond precision in astronomy. That plot for the binary star β Ari has been used in the well-known Bahcall Decadal Report (Bahcall 1991, Pan et al 1990) to support development of ground- and space-based interferometers. He also used an Echell spectrograph to obtain precise radial velocity measurements and determined an accurate distance to the Hyades prior to Hipparcos by combining the RV measurements with interferometric observations. In order to search for exoplanets with ground-based interferometers it is necessary to find candidates with reference stars within 20-30 arcsec. He has compiled a catalog of targets from more than 1200 Gliese stars having close reference stars with a dynamic range of 10 magnitudes. Since 1993 he worked on the Palomar Testbed Interferometer. His latest interferometric results (Pan, 2000) demonstrate that the distance to the Pleiades is consistent with other techniques and that the parallax measured by Hipparcos (116 +/- 3 pc) has ~10% systematic errors.

2.5 General Work Plan and Roles

This proposal requests 11 years of funding in support of the instrument scientist, a co-investigator, and a post-doctoral research fellow. The plan is to

a) identify the candidate targets that will best fulfill the science goals of the proposal. The stars will be identified through a combination of literature searches, analytical work, and simulations;
b) study and improve the GNAA approach, in particular we wish to improve the efficiency of the observations and gain a better understanding of baseline regularization errors;
c) work with the SIM science team and testbed teams to improve instrument calibration and invent new calibration procedures;
d) analyze data collected by SIM and report the results in scientific journals and presentations;
e) participate in public outreach and education programs.

Dr. Stuart B. Shaklan will serve as the instrument scientist and will participate in all phases of the plan.

Dr. Xiaopei Pan will contribute to target identification, the development of new science possibilities, data analysis and reduction, and public outreach.

A postdoctoral fellow will contribute to all phases of the work, with emphasis on the development of data reduction tools and data analysis.

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Appendix III. Statement of Work

This proposal requests 11 years of funding in support of the instrument scientist, a co-investigator, and a post-doctoral research fellow. The plan is to

a) identify the candidate targets that will best fulfill the science goals of the proposal. The stars will be identified through a combination of literature searches, analytical work, and simulations;
b) study and improve the GNAA approach, in particular we wish to improve the efficiency of the observations and gain a better understanding of baseline regularization errors;
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A postdoctoral fellow will contribute to all phases of the work, with emphasis on the development of data reduction tools and data analysis.

Data collected during IOC (the period up to 6 months after launch) will be made publicly available at the end of IOC. Scientific results from the long-term program will be publicly reported mid-mission (~ 2.5 years) and updated at the end of the mission (5 years).