The Space Interferometry Mission

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ABSTRACT

The Space Interferometry Mission (SIM) will be 10-m Michelson interferometer in Earth-trailing solar orbit. As a part of NASA's *Origins* program, it will be the first space-based optical interferometer designed for precision astrometry. As well as enabling forefront astronomical science, SIM will serve as a technology pathfinder for future Origins missions, such as the Terrestrial Planet Finder (TPF). SIM is being designed 4 microarcsecond (μas) precision absolute position measurements of stars down to 20 magnitude. Launch is currently planned for mid-2006, and the mission duration is 5 years.

By searching for the astrometric 'wobble' signature caused by a companion to a target star, SIM will be very sensitive to sub-stellar and planetary companions. By observing stars relative to nearby reference stars, an accuracy of 1 microarcsecond (μas) in a 1-hour measurement is expected, which is sufficient to detect planets of less than about three Earth masses around the nearest stars. With precision global astrometry, SIM allows parallax distance measurements to 10% accuracy, even on the far side of the Galaxy. During its 5-year mission, SIM will address a important variety of science questions relating to the formation and dynamics of our Galaxy. In addition to astrometry, SIM will demonstrate the technique of imaging using aperture synthesis. While this is routinely used by ground-based radio telescopes, a space-based optical synthesis imaging demonstration is the first step toward a later generation of large imaging telescopes. SIM will have resolution of 10 milliarcsec in the V band. It will also perform a demonstration of interferometric nulling, in which the on-axis starlight is suppressed to a level of 10^{-4}, a key requirement for TPF.

In this paper we outline the design of the SIM instrument, and how it will be used in the search for extrasolar planets. We also briefly describe some selected topics from the SIM astrometric science program.

Keywords: interferometry, astrometry, planet detection, astrophysics, Galaxy, parallax

1. INTRODUCTION

The Space Interferometry Mission (SIM) is a 10-m baseline optical interferometer operating in the visible waveband. The instrument is space-based to overcome the disturbing effects of the atmosphere on precision astrometry. SIM will extend the reach of precision astrometry to stars throughout the galaxy, and will thereby open up many areas of astrophysics. Searching for low-mass planetary companions to nearby stars is one of the most exciting of SIM's science goals. Measured in a local reference frame, SIM is expected to achieve an accuracy of 1 μas. In this mode, SIM will search for the astrometric 'wobble' relative to a nearby ($\leq 1^\circ$) reference star. In its global astrometry mode, SIM will provide 4 μasprecision absolute positions for stars down to 20 magnitude, with parallaxes to comparable accuracy. After the 5-year mission is completed, the proper motion accuracy will be about 2 $\mu\mathrm{as\,yr}^{-1}$, equivalent to detecting a stellar velocity of 10 m/s at a distance of 1 kpc.

The SIM design comprises three parallel simultaneous Michelson interferometers. The three baselines are parallel and close to coincident, but have different lengths. Figure 1 shows an outline of the SIM design. This design was recently selected over a design in which the three interferometers share a single baseline vector. The six siderostats (with one or two spares) reflect starlight into afocal telescopes which compress the beams from an input diameter of 0.3 m. Two interferometers track fringes on bright guide stars, to stabilize the optical system, and a third pair observes the science target. Light from each pair is directed to a beam combiner through as series of fold mirrors. A movable delay line adds optical path into one arm of the instrument, allowing the white-light fringes to be tracked. An internal metrology beam is used to measure the path difference between the two he. This path difference represents the fundamental astrometric quantity measured by SIM. An external metrology system on a 9-meter boom (Fig. 1 measures the length and orientation of the three baseline vectors, and tracks changes in their relative geometry. Each siderostat has a field of regard of 15° diameter; targets in the field are observed sequentially, while retaining attitude lock, using the bright guide stars tracked by the guide interferometers. Global astrometry is performed by measuring the change in white-light fringe delay, between targets. The key instrument and mission parameters are shown in Table 1.

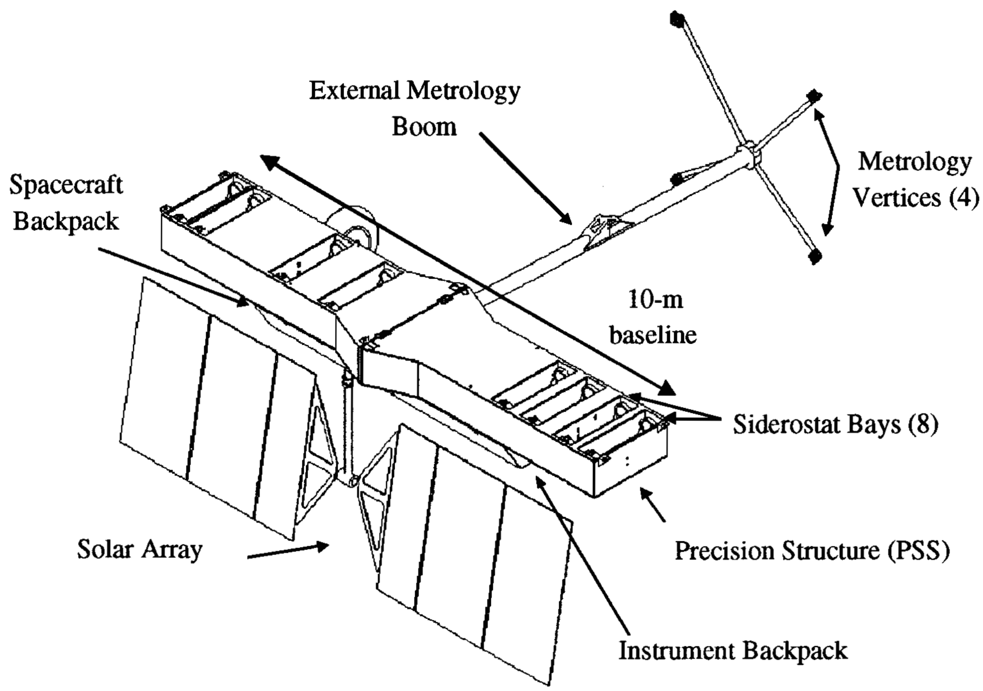

Figure 1. A sketch showing the main components of SIM, in its deployed configuration.

SIM will provide technology demonstrations for future NASA missions, specifically the Terrestrial Planet Finder (TPF). As the first optical interferometer in space, SIM will demonstrate many important functions, such as the operations of a relatively complex instrument, and the experience gained will be carried over directly or adapted. TPF will operate a nulling beam combiner, which will apply a polarization flip to one arm of the interferometer, which will yield cancellation of the on-axis starlight. SIM will carry a demonstration nuller, with the goal of achieving a null depth (on-axis suppression) of 10^{-4}. There are no scientific drivers for the SIM nuller, although the demonstration instrument could perform some interesting experiments.

SIM will be the first instrument to demonstrate aperture synthesis imaging in space. This technique is well-known in radio astronomy, with instruments like the VLA operating for many years. To fill in the 'u-v' plane, the instrument is rotated around the line of sight to the target. Small switchyard mirrors allow different combinations of siderostats to relay light to the science beam combiner, thereby providing different fringe spacing, and different angular resolutions. A sample 'u-v' plane plot is shown in Figure 2. The image resolution will be an unprecedented 10 milliarcsec (mas) in the optical. Although primarily a demonstration using a small fraction of the mission time, this observing mode is capable of some interesting science. For instance, a nearby active galactic nucleus with strong Hα line emission near its center. However, integrations times are long for astrophysically-interesting targets, because the collecting apertures, at 30cm diameter, are very modest by ground-based standards. An example of an imaging target for SIM is a nearby active galactic nucleus with strong Hα line emission near its center. SIM can probe the mass distribution in the very dense region near the central massive black hole by imaging the velocity structure of the line-emitting gas near the central 'engine' of the galaxy.

NASA has an interferometry technology development plan which includes laboratory testbeds, ground-based optical/IR interferometers, flight verification of components, and space-based missions. Its long-range goal of this program is to support the Origins scientific program, and future astrophysics missions, by a phased development which builds on experience gained, reducing mission cost and risk. The SIM web site at: `http://sim.jpl.nasa.gov/` contains more information on this mission, and interferometry technology at JPL. Other papers in this volume

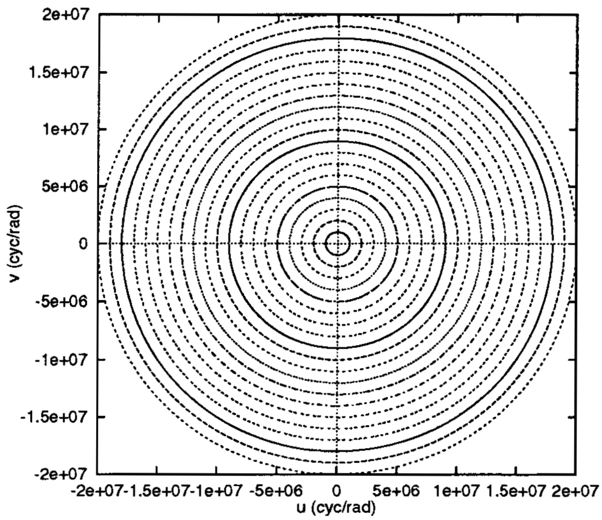

Figure 2. The aperture synthesis ('u-v') plane imaging with SIM, obtained by rotating the spacecraft, and by selecting siderostat pairs with differing separations.

describe the interferometry testbeds, and the technology developments supporting SIM.

Table 1. SIM Instrument and Mission Parameters

Baseline	10 m
Wavelength range	0.4 - 1.0 μm
Telescope aperture	0.3 m diameter
Astrometric Field of Regard (FOR)	15° diameter
Imaging field of view	0.3 arcsec
Detector	Si CCD
Orbit	Earth-Trailing solar orbit
Mission Duration	5 years (launch June, 2006)
Astrometry (wide-angle)	4 μas mission accuracy
Limiting magnitude (V band)	20 mag
Astrometry (narrow-angle)	1 μas in 1 hour
Imaging Resolution	10 milliarcsec
Interferometric Nulling	Null depth 10^{-4}

1.1. The search for planets around nearby stars

A wealth of data has become available on planets outside our solar system in recent years. These planets have been detected using the Doppler shift of stellar spectral lines due to the gravitational perturbation of the companions (see review by Marcy & Butler[1]). Very recently, one of these planets, in an edge-on orbit as seen from Earth, has been detected using photometry of the parent star, as the planet crosses the stellar disk.[2] These discoveries brings into focus a long standing problem, but poorly understood problem in astronomy, namely the formation of planetary systems. The study of star formation has long been an active research field, but until recently, extending our understanding to smaller-mass companions has been hampered by a lack of observational facts. But already these new data are being incorporated into a more comprehensive view of the formation of stars and planetary systems as related processes.

Many questions remain, and new questions are now being asked. SIM will contribute strongly to the observational database available for testing of solar-system formation theories, by searching for low-mass planets. these are hard to detect with radial-velocity techniques: the required precision is becoming comparable to the astrophysical 'noise' due to intrinsic variability caused by photospheric activity and rotation of the part] stars. SIM will be capable of detecting planets down to Earth mass around the nearest stars, and Jupiter-mass planets out to a kiloparsec. A key goal for the mission is to detect earth-sized planets orbiting nearby solar-type stars and study their characteristics. As one of the ultimate goals of this quest is the detection of life elsewhere in the universe, a further objective is to identify stars for the Terrestrial Planet Finder. By detecting extra-solar planets directly, TPF will be able to take low-resolution spectra of a planet's atmosphere. As noted in the Introduction, SIM serves as a technological precursor for TPF, in addition to providing targets.

For now, all detection techniques are indirect. Planets are extremely faint compared to the parent star – as much as 10^9 times fainter in the visible waveband. The well-known so-called 'wobble' of a star induced by a companion is the basis of both astrometric and radial velocity detection methods. With a resolution of the order of 10 meters per second, it has been possible to detect giant planets around several solar-type stars.[3,4] The mass of the planet is a lower limit, because of the unknown factor ($\sin i$) where i is the inclination of orbit plane. Astrometric detection in 2 dimensions allows a direct measurement of the inclination, and hence direct mass measurement, not a lower limit.

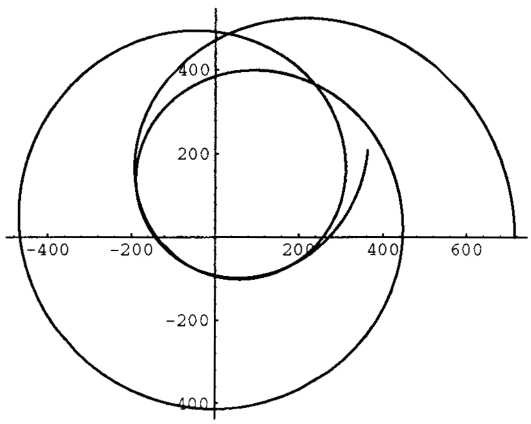

Figure 3. Planet searching with SIM by detecting reflex motion of the target star. Figure shows a face-on view of the solar system, as seen from 13.5 pc, relative to a local stellar reference frame. Axes are labelled in microarcseconds.

The astrometric signature of a gas-giant planet can be large. Figure 3 shows how the solar system would reveal itself to an observer at 13.5 parsec distance, if viewed face-on. The amplitude of this motion (after fitting for the proper motion of the star) is 500 μas, which is very large compared to SIM's single-measurement accuracy of 1 μas.

To detect a planetary companion, SIM will observe narrow-angle mode, which allows differential measurements at higher precision than global astrometry. The science interferometer alternatively observes the candidate star and reference stars within about one degree on the sky. These reference stars form a local frame, to which the star's motion is referenced. In this mode SIM will reach a precision of about 1 μasduring a 1-hour sequence of reference and target star observations. The reflex motion induced by an Earth-mass planets around the nearest few G-type stars is of the order of this accuracy. Because a two-dimensional orbit can be fitted, and the distance is known accurately via parallax, a unique mass can be determined, not subject to the inclination uncertainty of the radial velocity method.

Large terrestrial planets orbiting nearby solar-type stars should be detectable by SIM, if they are common, as well as Jupiter-mass and larger planets, which are already shown to be frequent [ref marcy and butler]. By building statistics, we can learn about the role of rocky cores in the formation and evolution of planetary systems. SIM can also investigate the frequency of planets as a function of spectral type. Since the astrometric sensitivity to planets depends mainly on distance, and very weakly on brightness (for stars brighter than about V = 10) a range of types can be studied. Radial velocity methods work best for late type stars (G, K, M), and less well on early types which are often have highly broadened lines due to rotation.

SIM would be able to detect all but two of the currently-known set of planetary companions. Most would be relatively easy targets for SIM, and having 3-dimensional orbits would allow precision masses to be determined for these systems. Since SIM's sensitivity improves for long-orbit planets (with periods less than about 5 years), it is complementary to the radial velocity methods in exploring the parameter space of orbit radius vs. companion mass. SIM will search for additional companions to stars with known planetary companions.

Recently, a triple-planet system was discovered around Ups Andromedae[5]. A 4.6-day companion 'b' had previously been detected, and two new companions 'c', and 'd', with periods of 242 and 1269 days have been confirmed. They have very similar radial velocity amplitudes. By contrast, the 'a' companion would be hard to detect, whereas the outer companions would have signatures of $90/\sin i$ μas and $560/\sin i$ μas – very easy detections for SIM. Figure 4 shows the appearance of the Upsilon Andromedae system, assuming a face-on orientation. If the system is inclined, then the planetary masses are larger, and the astrometric signature (in the orbital major-axis direction) would be larger than shown here.

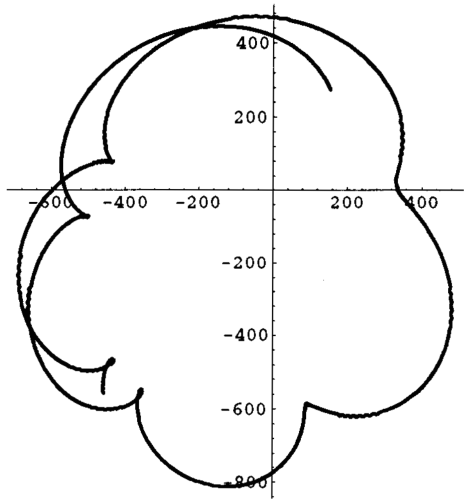

Figure 4. The Upsilon Andromedae planetary system, at a distance of 13.5 pc. The system inclination is unknown (and the individual orbits may not be co-planar). It is shown face on, but with orbits corresponding to the minimum possible companion masses [which would occur for an edge-on system]. Axes are labeled in microarcseconds.

The importance of SIM in studying systems like Upsilon Andromedae is twofold. First, SIM could search for low-mass planets in the same range of orbit radii as the outer planets already known. Such detections would provide key data in understanding the formation and stability of such systems, and models of their evolution. Second, SIM measures orbit inclinations directly. While the leading theory of planet formation from a protoplanetary disk strongly favors co-planar orbits, an experimental verification is essential for a meaningful test of models of the system stability.

2. PRECISION ASTROMETRY WITH SIM

While planet detection is one of the most important of the science objectives for SIM, the instrument is in fact capable of addressing a wide range of problems in stellar astrophysics, and galactic structure and dynamics. Because its accuracy will far exceed any currently planned instrument or space mission, there is great potential for unexpected results. These cannot, of course, be quantified now, so instead we summarize briefly some of the science areas which have been considered where SIM will have a major contribution to the field. With an absolute positional accuracy of 4 μas, SIM will improve on the best currently available measures (from the ESA Hipparcos mission) by 2 to 3 orders of magnitude, providing parallaxes accurate to 10% and transverse velocities accurate to 0.2 km/s anywhere in the Galaxy, to stars as faint as 20-th magnitude. With the addition of radial velocities from ground-based spectrometers, knowledge of all 6 position/velocity coordinates for objects of interest will allow astronomers to attack problems in stellar dynamics which are difficult without incomplete information. The recently approved FAME mission, led by the US Naval Observatory, will be the next large-scale astrometric instrument. It will complement SIM by observing a vastly larger sample of stars, albeit to lower precision, and lower limiting magnitudes. FAME will be ideally suited to programs which require data from a large sample of stars.

- *Stellar Dynamics of the Galaxy.* Using precision astrometry, SIM will address many fundamental questions concerning the mass distribution in our Galaxy, the dynamics of its stars, and the evolution of its stellar populations.

- *Dynamics of Small Stellar Systems.* The mass distribution of the Galaxy can be determined, by measuring the proper motions of globular clusters, or a sample of distant halo giant stars. This will help our understanding of the formation of the Galactic halo and the globular cluster system. Tidal tails from disrupted dwarf spheroidal galaxies also provide a powerful means of tracing the Galactic potential (Fig. 5).

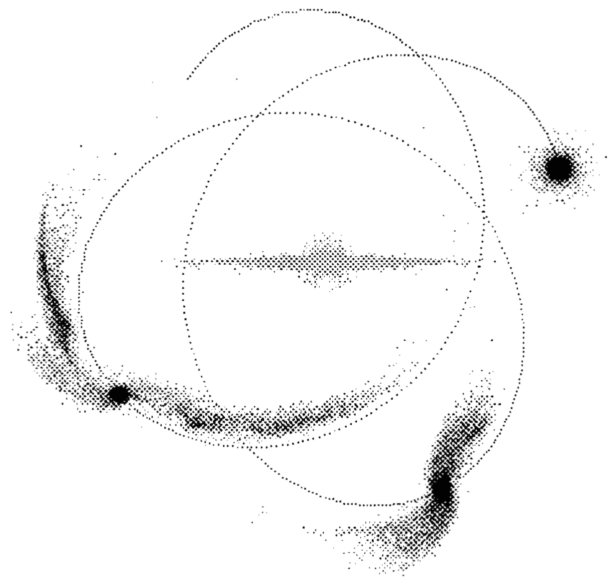

Figure 5. A simulation of the tidal interaction between 10^8 solar mass dwarf galaxy and the halo of the Milky Way galaxy. The disruption is shown at three positions along the orbit (dotted line), representing intervals of 1 Gyr. SIM would trace the motion of a small sample of stars in the tidal tail, to map out the interaction. Simulation courtesy of Kathryn Johnston[6]

- *Brown Dwarfs and Massive Planets.* SIM will be able to detect sub-stellar companions (gas giant planets and brown dwarfs) around a large sample of nearby stars, and neutron stars and black holes around more distant stars, by measuring their astrometric perturbation on the primary star.

- *Calibration of the Distance Scale.* By measuring precise parallax distances, SIM will calibrate the luminosities of Cepheid and RR Lyrae 'standard candle' variable stars, eliminating the usual uncertainties in distance determination. Current uncertainties in these standard candles significantly limit the accuracy of the Hubble constant.

- *Ages of Globular Clusters.* SIM will measure the distances to globular clusters directly using trigonometric parallax, and hence the luminosities of the oldest main-sequence stars in globular clusters can be determined, including subtle effects due to reddening and metallicity. Stellar evolution models for clusters apparently conflict with the age of the universe inferred from the Hubble expansion; SIM will help greatly reduce the age uncertainty.

- *Masses and Evolution of Stars in Close Binary Systems.* By detecting the astrometric signature of the binary star orbit, SIM can determine the masses and orbits of a large number of ordinary binary star systems, as well as more exotic systems: white dwarf/CVs, neutron stars and black holes.

- *Rotational Parallaxes.* SIM will be able to detect the rotation of stars in the disks of nearby spiral galaxies.[7] These provide a method of distance determination without use of luminosity-based indicators. This method is analogous to that of orbital parallaxes of binary stars.
- *Gravitational Microlensing.* The astrometric signature of microlensing events caused by massive compact halo objects (MACHOs) along the line of sight is the counterpart of the well-known photometric detection method.[8] Masses for these objects can be inferred, providing important clues to the nature of dark matter in the Galaxy. These would be scheduled as 'targets of opportunity' for SIM.

3. CONCLUSIONS

As NASA's first astrometric interferometer in space, the SIM will open up many areas of astronomy, most notably the detection of low-mass planetary companions to nearby stars, and serve as a technology pathfinder for future astrophysics missions. SIM is one of the key missions in the NASA's *Origins* theme, which searches for the beginnings of the universe, how galaxies and stars - and planets - formed and will evolve.

ACKNOWLEDGMENTS

SIM science is very diverse, and the proposed science program has evolved over a number of years. The breadth of the opportunities are the results of the efforts of many astronomers who have explored the potential of microarcsecond astrometry, and especially SIM Science Working Group (co-chairs Mike Shao and Deane Peterson) who developed many of the science topics presented here. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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