2 Astrometry

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2.1 Introduction

Astrometry is a powerful tool for detecting and characterizing exoplanet systems. So far, its role has been primarily to provide unambiguous masses for planetary systems like 55 Cnc and Epsilon Eridani which were originally discovered with radial velocity surveys. In the past few years, there have been ground-based efforts to detect Jovian planets around low mass stars and binary systems. However, ground-based radial velocity programs remain the primary method for the detection of Jovian planets; the first such system detected by astrometry still eludes us. Due to the systematic nature of the intrinsic jitter inherent to all stars due to starspots, granulation and faculae, radial velocity measurements are unable to reach the sensitivities necessary to detect terrestrial planets in the habitable zones of our nearest solar-type stars. This is possible, however, with micro-arcsecond astrometry. Only micro-arcsecond astrometry can detect habitable Earth-like planets around nearby Sun-like stars while simultaneously measuring the planet masses, the most fundamental quantity for characterizing exoplanets.

The 2008 Exoplanet Forum Committee on Astrometry strongly supports the recommendations of the Exoplanet Task Force (ExoPTF) Report and the past three Decadal Surveys. ***The Committee's highest priority is to deploy a facility for micro-arcsecond astrometry of nearby stars during the 2010–2020 decade***, with primary goals of finding Earth-like planets and characterizing the structures of planetary systems. A micro-arcsecond astrometry program will support a variety of science programs outside the field of exoplanets; the Committee strongly supports a mission design that will enable these non-exoplanet-related research efforts. The technology development efforts of the past few decades have provided a system architecture capable of this micro-arcsecond astrometry goal. The key technology milestones have been achieved. It is now time to deploy the facility itself.

The ExoPTF also made several smaller recommendations for the role of astrometry in exoplanet studies over the next decade. These secondary science programs have more modest budgets, but make smaller contributions to the understanding of planetary systems. A number of these secondary science goals are supported by the committee, which finds that *these should be pursued, but only if doing so will not delay the deployment of the highest priority micro-arcsecond astrometry mission.*

2.1.1 A Micro-arcsecond Astrometry Mission

All the highest priority science programs considered by the astrometry committee are addressed by a single, ~5 year or longer astrometry mission capable of micro-arcsecond precisions.

On page viii of their draft report, the first recommendation the ExoPTF makes for the 6–10 year (2014–2018) timeframe is to "Launch and operate a space-based astrometric mission capable of achieving 0.2 micro-arcsec sensitivity to planet signatures around of [sic] 60–100 nearby stars." The past three decadal surveys have promoted development of a micro-arcsecond astrometric program for detecting and characterizing exoplanets. *The astrometry committee recommends that the 2010 decadal survey continue strong promotion of a micro-arcsecond astrometry mission, to be deployed in the early part of the 2010–2020 decade.* Those past decadal surveys resulted in strong support for technology development efforts to design such a mission. All key development milestones for an astrometric mission based on the Space Interferometry Mission (SIM) architecture (including SIM-Lite (Goullioud 20XX) and Planet Hunter (NASA ROSES Advanced Strategic Mission Concept Study, now underway)) have been accomplished, and the community is ready to capitalize on this significant investment. Further delay may waste this investment, as the current experts could be lost to other pursuits.

Table 2-1. Astrometric Mission Concepts

Mission Name	Science Topics	Planet Mass Sensitivity, 10pc	Number of Stars for Terrestrial Planet Sensitivity
SIM	Exoplanets and Other Astrophysics	0.5 Earths	120
SIM-Lite	Exoplanets and Other Astrophysics	0.7 Earths	85
Planet Hunter	Exoplanets Only	0.7 Earths	85

Science Goals

Support for Micro-arcsecond Astrometry Science Other Than Exoplanets

A potentially surprising result of an internal survey of committee members was *unanimous support for the non-Exoplanet related science that an astrometric mission will address*, despite the fact that all the scientists being surveyed work specifically in the field of exoplanets. Committee members found that this was important both for maximizing the science output and to make a major mission attractive to the astronomical community as a whole. There has been some misperception that the scope of an astrometry mission is limited to exoplanets or a few other niche topics. The committee wishes to emphasize that a micro-arcsecond astrometry mission *is* a general purpose observatory that will open up an new discovery space for a broad range of topics in astrophysics.

The SIM-Lite mission is a direct descendent of AIM, the astrophysics mission endorsed by the 1990 Bahcall Report, and re-confirmed by the 2000 McKee-Taylor Report. This mission was originally recommended based on its promise of addressing a wide range of problems in stellar and galactic astrophysics. Planet detection, in 1990, was posed only as an interesting possibility, rather than a major science driver.

SIM-Lite, in addition to addressing the recommendations of the ExoPTF, is fully capable of performing the science laid out in the McKee-Taylor Report. Indeed, the critical importance of precision astrometry has not diminished in the intervening years. The expected ESA mission named *Gaia* will conduct a large astrometric survey, building on the recognized ground-breaking work of Hipparcos. As a flexibly-pointed mission capable of very high astrometric precision (4 μas positions) at faint magnitudes ($V < 19$), SIM-Lite occupies a very different parameter space from *Gaia*. A recent peer review of the SIM Science Team Key Projects (SIM Book 2008) showed that with minor exceptions, the broad astrophysics case for SIM remains unsurpassed by any current or planned future mission.

The science case for SIM PlanetQuest is laid out in considerable detail in the Science Team's paper (Unwin et al. 2008). SIM-Lite replaces SIM PlanetQuest as a cost-effective way to do 'precision astrophysics'. It has essentially the same accuracy as SIM PlanetQuest, but can observe approximately half the number of sources in the faint-source limit (this does not apply to the exoplanet mission, where the stars are all bright). In most cases, the Science Team is able to do the same science but with a judicious re-allocation of planned observing time.

Formation and Mass Distribution of the Milky Way

Tidal tails of dwarf spheroidal galaxies form an exquisitely sensitive tracer of the interaction history of the Galaxy, and also the detailed shape of its potential, but only if one has good 3-space positions and 3-space velocities. SIM-Lite uniquely provides 2 of the 3 space velocity components in distant tails (radii > 20 kpc). This technique can be extended to the Local Group (out to ~5 Mpc) through astrometry of the brightest supergiants in member galaxies, providing key data on the mass distribution and dynamics of the Local Group.

Stellar Astrophysics

The masses of stars at each end of the main sequence are not well characterized. Many of the estimated stellar masses have 10% errors, which is insufficient to challenge models of stellar luminosity and evolution. Many 'exotic' stars such as the components of X-ray binaries have distances, masses and luminosities crudely estimated to a factor of two. These are simple, but absolutely fundamental measurements that would be straightforward for SIM-Lite to complete.

Quasar Astrophysics

At optical wavelengths SIM-Lite will probe the internal structure of quasars to complement the highest-resolution VLBI imaging. Thirty years after the discovery of superluminal radio sources, many fundamental questions about the formation and propagation of jets still remain unanswered. Precision optical astrometry, although not able to resolve a quasar core, will sense variability in a waveband orders of magnitude away from the radio, and probe a regime where accelerated particle lifetimes are very short. Variability and differential color shift across the optical band are vector quantities that can be compared with other geometric and structural information in quasars.

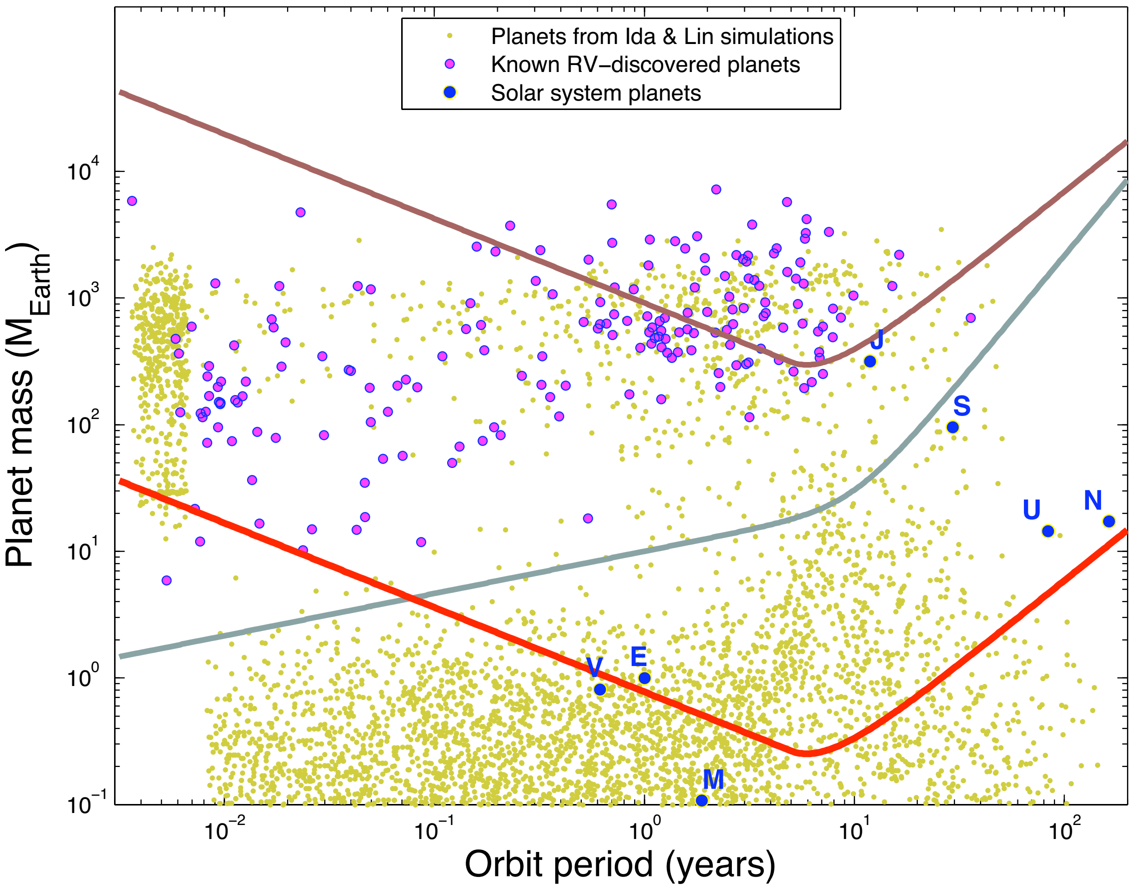

Figure 2-1. Plot of the expected sensitivity of different planet detection techniques as a function of planetary mass in Earth-masses with the period in years. The grey curve represents radial velocity programs with a measurement accuracy of 1 m s^{-1}. The brown curve is the average sensitivity of the *Gaia* mission at 70 μas. The red curve represents the median target sensitivity of the SIM-Lite mission assuming a sample of 60 optimized targets. The blue dots show the properties of our solar system planets, the purple dots are the properties of known RV-discovered planets and the yellow dots are the planets produced through the core accretion models of Ida & Lin (2004a, 2004b, 2005). (J. Catanzarite, JPL)

Detecting and Characterizing Low-Mass Planets

The study of exoplanets is driven by our desire to better understand the origins of life and our place in the universe. Is the phenomenon of life unique to Earth, or is it commonplace? Life as we know it requires a few crucial ingredients that one would expect to find on habitable exoplanets, foremost being water that remains liquid over geological timescales. Only a small range of star-planet separations are suitable for liquid water. While some exoplanets have been found within the habitable zones around other stars, they have all been gas giants like Jupiter; current techniques being insensitive to the smaller signatures that result from small terrestrial planets. Only for the nearest stars will it eventually be possible to separate the planet light from the starlight to study the atmosphere of an Earth-like planet, thus it is reasonable to prioritize our search for exoplanets to the nearest stars. Knowing a planet's mass will be important to reliably interpret its spectrum. Thus the path to identifying candidate habitable planets requires a observatory capable of addressing four requirements: it must (1) search the stars closest to the Sun with enough sensitivity to (2) detect Earth-sized planets at (3) star-planet separations that allow for liquid water and (4) measure their masses. The micro-arcsecond astrometry mission meets each of these requirements.

As is shown in Scargle (1982), to achieve a false alarm probability of about 1%, within a factor of two, for a number of measurements that ranges from tens to thousands, the signal to noise ratio (SNR) needed is about 5.5 to 6.0, depending slightly on the number of measurements. If σ is the one-axis RMS noise per differential measurement, N is the number of visits, and α is the amplitude of the astrometric signature that can be detected with a probability of 50%, then

$$\alpha = SNR \times \sigma / N^{1/2} \qquad \text{or} \qquad N = (SNR \times \sigma / \alpha)^2 .$$

For example, the Earth's astrometric signal amplitude at 10 pc is $\alpha = 0.3$ μas. For an RMS measurement uncertainty of $\sigma = 1.4$ μas, $N = 659$ measurements are needed to detect an Earth with an $SNR = 5.5$. A targeted mission is therefrore required with micro-arcsecond single-measurement precisions, a noise floor below 0.3 μas, and the ability to target the closest and brightest stars.

Precision radial velocity monitoring of the most promising candidate stars, beginning now and extending through the end of the astrometric mission, will maximize mission success and offer a more complete description of the planetary systems we will explore.

Operate as a Precurser Mission for a Future Direct Imaging Program

Recent technological advancements have led us to the point where mankind might finally answer the ancient question "Are we alone?" by searching for evidence of life on planets around nearby stars. Terrestrial planets of 0.3–10 $M_\oplus$ would provide the best conditions for habitability, as heavier planets could have unfavorably thick atmospheres, and lighter ones might not have any atmosphere at all. Orbits in the range 0.85–1.6 AU around a star of solar luminosity would offer planetary temperatures compatible with liquid water. For other stellar luminosities, the "habitable zone" orbits scale roughly as the square root of the luminosity. Although M dwarfs are more common than other stars, they may not be favorable targets, because their habitable zones reside in close-in orbits and their planets may be tidally locked, reducing their likely habitability. Nearby Sun-like stars are preferable targets, and also more amenable to study by follow-on optical and infrared direct imaging missions.

The first step is to locate suitable candidate planets. *A micro-arcsecond astrometry facility is the most feasible method for identifying candidate Earth-like planets around nearby Sun-like stars in the 2010–2020 decade.* Radial velocity surveys are limited by the intrinsic surface jitter of stars that masks the tiny radial velocity signature (~10 cm s^{-1}) of a habitable Earth-like planet. Transit surveys are only sensitive to planets whose orbits are edge-on as seen from Earth, and thus will transit their star; the likelihood of which is very small (< 1%) for planets in the habitable zones of Sun-like stars, and so many nearby planetary systems would not be fully explored. Direct imaging missions are observatories to measure the spectra of exoplanets, and it would be inefficient to devote a large fraction of their observing time solely to finding planets. Other planet detection methods are less well optimized for studying nearby stars.

The second step is to obtain spectra of the planetary atmospheres, looking for signatures related to life on Earth, such as water and oxygen. The greatest challenge for the success of such a mission is the combination of the extreme contrast between and small separations of star and planet and the intrinsic faintness of the planet. The most reasonable targets for a direct imaging mission are nearby stars where this challenge is minimized (though still quite formidable). *Astrometry is well optimized for identifying low-mass planets around the nearest stars, the best targets for direct imaging missions.*

The ExoPTF report states on page 55 "The most promising way to mitigate the cost of space-based direct imaging is 1) to identify targets before the direct imaging mission is flown." The astrometry committee agrees with this assessment. By first deploying an astrometric mission to find and measure the orbits and masses of Earth-like planets around nearby stars, the cost of a future direct imaging mission can be minimized and the scientific output greatly increased.

Where to look: Identify nearby targets

The best way to search for potentially habitable exoplanets around nearby stars is indirectly—by looking for the astrometric wobble of the star responding to the gravitational tug of the orbiting planet. The minimum required single-measurement astrometric accuracy is ~1 μas.

The alternative—a direct search by coronographic images—is problematic. The first problem is the central obscuration, which hides large fractions of most orbits. Only for a fraction of the planet's orbit is it correctly positioned where a coronograph will detect it. The second problem is the low information rate, demanding many long exposures with rare positive results, assuming a planet is present. The third problem is the difficulty—or even impossibility—of estimating the planetary orbit from the small number of measurements that can be obtained in the epoch of discovery, typically only 6 months long due to solar avoidance. Without knowing the planetary orbit, science operations become a matter of guess work, and any planet found will probably be lost.

The ExoPTF recognized these difficulties with the direct planetary search when it recommended splitting the finding and characterizing tasks between two concatenated programs, an indirect finder program and a direct characterizer program. The direct imaging mission will characterize planets found by the finder program. While the indirect finder program can stand alone and still provide valuable science content without the direct imaging program, the direct imaging mission will not have identified targets if the indirect finder is not deployed first.

When to look: Characterizing Orbits

Astrometric observations of stars hosting Earth-like planets allow the orbits to be determined. The position of the planet can be predicted as a function of time. This provides a solid basis for future planning direct imaging programs, as the observing schedule can be set to look at targets when the star and planet are most optimally configured for isolating light from the planet.

The direct imaging program will operate more efficiently by only observing when the planet-star configuration is likely to produce a positive detection and spectrum of the planet. No time is wasted searching a target when the orbital configuration is poor. The technical requirements of a direct imaging mission may be reduced because it need only meet requirements for detecting planets when they are in optimal configurations.

Characterize Planets Targeted By Imaging: Masses

On page 55, the ExoPTF report finds "a capability to determine mass, specifically space-based astrometry described above, is necessary in conjunction with the direct imaging platform." The astrometry committee agrees that without this capability, the science returns of a direct imaging mission are marginalized.

A mass estimate derived from an orbital solution of astrometric data from an astrometric "finder" mission would be fundamental to our understanding a planet's characteristics. Knowledge of a planet's mass provides the context for interpreting any spectrum of a planetary atmosphere measured by a direct imaging mission, and so would be crucial to determining whether a planet can support life. Only by measuring the gravitational effect of a planet on its host star can the planet mass be measured. Direct imaging and transit light-curve observables do not provide measurements of planet mass, and model-based estimates are a poor substitute, because they require that the characteristics of exoplanets follow the patterns seen in our own Solar System.

Multiplanet Systems and Planetary System Architecture

Theoretical models of planetary system formation inevitably produce systems with multiple planets. Combined with the Doppler discovery of exoplanet systems with at least four (HD 160691) or five (55 Cnc) planets, and the eight planets in our Solar System, it is clear that we should be prepared to discover that multiple planet systems are more likely to be the rule than the exception. While the number of gas giant planets around F, G, and K stars is beginning to be well understood from Doppler detections (Cumming et al. 2008), there are only weaker constraints on Neptune-mass planets, and no constraints at all on Earth-mass planets. Using our Solar System as a guide, one expects that long-period Jupiters should be accompanied by inner terrestrial planets, and it has even been suggested that short-period, hot Jupiters might be orbited by habitable terrestrial planets, in spite of the prior migration of the Jupiter-mass planet through the habitable zone of the star (e.g., Raymond et al. 2006). The basic theoretical expectation is that terrestrial planets should be commonplace, regardless of whether or not gas giant planets have had a chance to form (Wetherill 1996). If multiple planets are known to orbit a given star, we can place strong constraints not only on the orbital stability of the entire system, but also upon the mechanisms involved in the planet's formation and orbital evolution, and so discovering and characterizing multiple planet systems are important goals for exoplanet searches.

Astrometric observations provide the opportunity to measure six phase-space coordinates for each planet detected. In particular, by measuring the orbit's inclination, astrometry can provide the planet-star mass ratio with no degeneracies (except for pathological geometries). The precise measurements of planet mass is key to understanding the dynamical state of multiple planet systems. Therefore, intensive monitoring of multiple planet systems should be one of the key science drivers for an astrometric mission.

If we have only radial velocity data, we can nontheless by assuming the system is dynamically stable constrain the inclinations to provide upper limits for the planet masses. Unfortunately, such analyses often leave uncertainties of order ~30 degrees in inclination and a factor of ~2 in the planet masses. These uncertainties can cause even *qualitative* uncertainties in the dynamical state of the system (e.g., mode of secular evolution, being in or near a mean-motion resonance). With sufficient observations, astrometric observations can resolve such degeneracies, so that dynamical modeling can constrain the formation and orbital evolution of multiple planet systems. For example, different mechanisms for eccentricity excitation make different predictions for the degree and circumstances of inclination excitation. Therefore, dynamicists look forward to astrometric measurements of the relative inclination between planets and whether this correlates with planet mass, orbital period, eccentricity, and/or presence of a binary companion.

Both the number and fraction of planets in multiple planet systems is set to increase as planet searches become sensitive to planets with lower masses and longer orbital periods. Since many, if not most, planets are members of multiple planet systems, understanding the formation and evolution of multiple planets systems is essential for understanding planet formation in general. With sufficient astrometric observations of a multiple planet system, the current planet masses and orbits can be precisely measured, so that theorists can investigate the secular orbital evolution and gain insights into planet formation. For example, different models of planet migration and eccentricity excitation make different predictions for the secular evolution of planetary eccentricities and inclinations. Therefore, theorists look forward to astrometric observations that determine if the mode and amplitude of secular inclination evolution correlates with the mode and amplitude of secular eccentricity evolution. Searching for such a correlation could test whether certain features in the secular eccentricity evolution (previously identified by radial velocity observations) are reliable fingerprints for recognizing the outcomes of various planet formation models.

A remarkable feature of our solar system is its coplanarity. Thanks to the recent redefinition of “planet”, all planets in the solar system are coplanar to within 7 degrees. If this is a general feature in most planetary systems, it is a strong observable constraint that must be matched by planetary system formation and evolution models. However, with the coplanarity of only one system (ours) being known, it is impossible to tell how common this feature is in nature.

Studying additional multi-component solar systems will serve to expand our understanding of what a typical solar system geometry might look like, and whether the distribution of geometries even allows for “typical” to be defined. It is interesting to note that while the distribution of relative inclinations of triple stars systems is slightly biased toward coplanarity, the systems tend not to be as well aligned as the planets in our solar system.

Flexible scheduling can greatly aid the characterization of multiple planet systems. For instance, a Solar System “clone” would be recognized as especially interesting, but complex, after about two years. Such as system would easily warrant an increase in observing cadence during years 3–5 of a mission.

Micro-arcsecond Astrometry in the Context of Other Exoplanet Programs

While the astrometry committee strongly supports a direct imaging mission after completion of a micro-arcsecond astrometric finder program, *if it comes down to choosing either one or the other, an astrometric mission is a higher priority than imaging.* The committee favors a plan of deploying an astrometric mission in the early part of the 2010–2020 decade, with a direct imaging mission be deployed at the end of the decade or early in the 2020–2030 timeframe.

The imaging mission science would be compromised without an astrometric mission, because the astrometric mission would provide a comprehensive target catalog. An imaging mission by itself would have a greatly reduced science throughput and consequently would be more expensive and less efficient. Moreover, from imaging data alone, masses it would not be possible to determine masses, and it would be difficult to interpret imaging results.

Science Requirements

Planet Finding

The Exoplanet Task Force report recommended an astrometric mission with the capability to achieve a mission minimum detectable astrometric signature of 0.2 μas after many hundreds of measurements, derived from the desire to detect a one Earth mass planet at the inner edge of the habitable zone for a Sun-like star located at 10 pc, and having a throughput sufficient to survey 60 to 100 nearby stars to this depth during the mission lifetime in order to generate a sufficient number of candidate planets for a later direct detection mission.

These recommendations can be met by an astrometric mission capable of carrying out a roughly five-year mission while achieving the recommended astrometric precision for target stars from –1.4 V_{mag} through 7 V_{mag} that each have reference stars (typically K giants at ~1kpc) brighter than ~10 V_{mag} located within two degrees of the target star on the sky.

We note that the actual program undertaken by an astrometric mission would of course be informed by all prior knowledge, most notably the frequency of terrestrial planets discovered by *CoRoT* and *Kepler*. A flexibly pointed instrument can be adapted to maximize the science return.

Other Areas of Astrophysics

One of the more general purpose versions of the micro-arcsecond astrometry mission guarantees the best science return for the investment. An astrometric mission only capable of meeting the recommendations for planet finding would not be capable of achieving significant strides in other areas of astrophysics as recommended by the two previous NRC astrophysics Decadal Surveys, primarily because the interesting astrometric science lies in the dim star regime out to 19 V_{mag}, which cannot be reached by other ground or space missions. Achieving the astrophysics recommendations of the prior Decadal surveys requires the stability to support much longer integration times than required to achieve only planet finding.

2.1.2 Other Strongly Supported Recommendations

Science Goals

Theory

As noted in the Report of the ExoPTF, there is a clear need to combine observational advances in detecting and characterizing exoplanets with theoretical work that supports these discoveries in several ways. The astrometry committee focused on theoretical work of most importance for astrometric planet discoveries, as opposed to, e.g., direct detection, where the theory of exoplanetary atmospheres becomes important.

Theoretical work on orbital dynamics is essential for determining the best fit for the exoplanet orbits, determining orbital stability over long time periods, understanding orbital resonances and how they formed, and determining the interactions in multiple planet systems where some planetary orbits are poorly constrained or completely unknown.

Theoretical work on planet formation mechanisms across the entire range of planets, from terrestrial planets, to ice giants, to gas giants, is necessary in order to place the exoplanet discoveries in the context of planetary system formation theories. We expect that terrestrial planet formation is strongly influenced by gas giant planet formation and orbital evolution, so a complete theory of planet formation is needed in order to understand the formation of any one component. Theoretical models provide testable predictions of what might be discovered, and therefore help to define the next steps in a long-term program of exoplanet discovery and exploration.

Understanding the extent of habitable zones around astrometric target stars will focus our attention on the best targets to search for the possible detection of habitable worlds. Recent theoretical work, e.g., has highlighted the potential of low-mass, M dwarf stars as hosts for habitable worlds (Tarter et al. 2007).

The Impact of Gaia

On page 54 of the ExoPTF report, the ExoPTF finds "The European *Gaia* space mission will be a useful demonstrator of the ability to do spaceborne astrometry to find giant planets, and will contribute to the census of Jovian-mass planets around Sun-like stars." The committee agrees *Gaia* is an exciting program, but finds that its existence has little impact on setting priorities for other astrometry programs because it operates in a complementary—rather than duplicate—capacity to those programs.

Gaia is a European astrometry mission with planned launch for 2011. It will achieve 100 μas per-measurement precisions (to $V = 15$) on 30 million stars (and reduced precision for up to a billion fainter stars), with each star revisited 1–250 times (typically ~90 one-dimensional measurements) over the course of the mission. It is a survey mission without capability to be pointed at a particular object, meaning the number of revisits cannot be increased for a high priority target. *Gaia* will saturate for very bright stars ($V \sim 6$), including the stars closest to Earth that are the highest priority targets when looking for Earth-like planets.

The measurement precision of Gaia is insufficient to discover Earth-like planets; the 100 times better precision of a micro-arcsecond astrometry program is required to achieve this goal. Furthermore, the number of repeated measurements for a given target is much larger for a pointed mission (with perhaps 200–500 (two-dimensional) measurements on high priority targets), which will both improve the sensitivity to lower mass planets, and provide better coverage of a planet's orbit. Good orbital coverage is necessary to adequately characterize a planet's orbit well enough to predict when the best observing time will occur for future missions.

Detecting Large Numbers of Giant Planets

The discovery of the first giant exoplanet (Mayor & Queloz 1995) occurred only 13 years ago. This discovery opened up the field of exoplanet research. Currently over 300 giant exoplanets have been identified around nearby stars. These have provided initial statistics on the properties of giant planets. In order to make a substantial impact on these statistical studies, future efforts will require detection of an order of magnitude more objects.

A sub-milliarcsecond astrometric program can discover and make dynamical mass measurements for hundreds of giant exoplanets down to the mass of Jupiters. This would significantly supplement the results from the past years of radial velocity searches, transit searches, and microlensing searches. It is worthwhile to greatly increase the numbers of planets to enable class studies with enough planets to come to conclusions about physical properties and frequencies in each of the different categories, e.g., spectral type, age, and metallicity.

MIDEX or Discovery Class Space Survey

An astrometric space-based system that is in the MIDEX or Discovery class can make a significant contribution in the area of giant exoplanets. Companions down to Neptune mass can be discovered around thousands of stars with the added precision and stability of space observations (Pravdo et al. 2007). An infrared mission in space could for the first time do a broad survey of exoplanets around low-mass and young stars. It would be complementary to *Gaia* both in low-mass stars that *Gaia* has difficulty observing, and for bright stars that could be observed with a high-dynamic range instrument but not *Gaia*.

An example of this class of mission is Giant Planets around M, L, and T Dwarfs in the Infrared (*GIMLI*). *GIMLI* targets low-mass systems and can thus help settle the debate over the dominant formation mechanism for EGPs (e.g., core accretion or disk instability), illuminate the differences between brown dwarfs and high-mass planets, and provide a calibration of the mass-luminosity relationship for the lower end of the stellar main sequence. *GIMLI* features a 1.4-m aperture with a high-dynamic range IR instrument that performs narrow-angle astrometry with 50 *μas* precision. It can also accommodate a complementary coronagraph. It is sensitive to exoplanet masses down to < 0.01 Jupiters, i.e., Uranus- or Neptune-masses for nearby older stars and for younger stars in the nearby star-formation regions.

Ground Based Optical Astrometry

Single-telescope ground-based astrometry has had success in discovering stellar and brown dwarf companions and measuring their dynamical masses (e.g., Pravdo et al. 2004; Pravdo, Shaklan & Lloyd 2005; Pravdo et al. 2006), but no exoplanet has yet been astrometrically discovered. The reasons for this are simple: lack of support for observing time and lack of funding for instruments. These indirect observations have demonstrated the required sensitivity to detect large exoplanets but need a minimum of observing time for adequate time-sampling. A modest fraction, e.g. 10%, of the time currently granted to radial-velocity (RV) observations would result in the first astrometric discoveries of exoplanets.

Dynamical mass measurements could be made of > 50 of the currently known exoplanets with ambiguous mass measurements (due to unknown inclination angles) with a new ground-based system featuring a detector with high dynamic range. Such an instrument could use current technology either in the visible or infrared. An infrared system would have the added advantage of opening a new region of discovery space, *viz.* exoplanets around low-mass stars. Since low-mass stars comprise 70% of all stars this activity would be an important component of the desired census of exoplanets. The discovery of exoplanets around low-mass stars is inadequately addressed by current programs. RV programs have demonstrated poor sensitivity to long-period (> 1 yr) planets around low-mass stars, and the detection of such planets with other techniques, e.g. transits and microlensing, has very low efficiency. An infrared camera built with existing technology, operating with adequate observing time on a large-aperture ground telescope can detect planets around many low-mass stars, greatly increasing the ~10 systems that are currently known.

In a recent paper (Cameron et al. 2008) it was demonstrated that 100-μas astrometry can be achieved in few-minute observations using the Palomar 200" PALMAO adaptive optics (AO) system in K-band. The paper articulates the problem of differential AO astrometry in the face of the dominant noise source (which is correlated tilt anisoplanatism), derives its expected contribution to the astrometric uncertainty, develops an optimal estimation algorithm for performing astrometry, and verifies the expectations with extensive on-sky tests at Palomar and Keck. The technique achieves ~100-μas precision in 2 minutes and ~100-μas repeatability over 2 months. The technique is currently being used at Palomar to search for planets around mid-M-dwarfs.

The European Very Large Telescope Interferometer (VLTI) began commissioning the PRIMA narrow-angle differential astrometry instrument in August 2008. The most optimistic estimates predict 10–20-μas performance. This will be an excellent tool for characterizing giant planets around nearby stars, and the expected long lifetime of this program will allow it to capitalize on astrometry's increasing sensitivity with planet orbital period. The committee agrees with the ExoPTF's conclusion that, for ground-based observatories, there are “no other facilities that would match or exceed the performance of VLTI within the 15-year time frame” (page 101). The VLTI will operate in the near-IR, and can study objects obscured at visible wavelengths including protostars and the galactic center.

The two 10-meter Keck Telescopes have been combined as an interferometer. Project ASTRA, funded by the National Science Foundation (NSF), is building a differential astrometry module for the Keck Interferometer. The resulting astrometric precision is expected to be on the level of hundreds of micro-arcseconds. The small amount of time available for interferometry on these large telescopes limits its impact to very specific observing programs, such as RV-identified multiplanet systems or the galactic center.

Lifting the Mass/Inclination Ambiguity for RV-Identified Exoplanets

The large majority of known exoplanets have ambiguous masses: their unknown inclination angles constrain the results to lower mass limits only. This mass ambiguity disappears in the astrometric determinations of dynamical mass, because astrometry determines the system inclination angles. Specific targets of interest where unambiguous masses are important include those with multiple planets where planet-planet interactions might become significant. The inclination ambiguity does not strongly affect statistical distributions of planet masses. However, for samples of a large number of planets it is also important to know where each of the systems lies in the parameter spaces defined by theorists. Ida et al. (2004, see Figures 9 and 12) demonstrate how knowledge of unambiguous dynamical masses can guide development of theory. The statistical assignment of inclination angles to many systems degrades the quality of the solutions, especially when the number of planets is limited to a small number of planets in each category of the multidimensional (spectral type, age, metallicity, etc.) parameter space.

2.1.3 Recommendations Addressed by the ExoPTF that Here Have Mixed or Ambivalent Support

Astrometry at Radio Wavelengths

Most stars are faint at radio wavelengths. A few active stars can be detected in non-thermal emission by the VLBA. Operating at shorter wavelengths, ALMA will detect thermal emission from many main sequence stars. However, its limited resolution will restrict astrometric precisions to the milli-arcsecond level. This may be useful for the study of giant planets, but is limited in its scope. The Square Kilometer Array (SKA) will have the sensitivity required to detect main sequence stars, and its current international specifications include very long baselines that would enable astrometry at micro-arcsecond precisions at centimeter wavelengths. However, there is concern that any non-thermal emission, which may not be centered on the star itself, will reduce the astrometric precision, potentially to the level of hundreds of micro-arcseconds.

The committee generally supports radio astrometry as a useful method for exoplanet detection only if it requires a modest marginal cost to implement at existing facilities. The impact of radio astrometry on the field of exoplanets is unlikely to be substantial enough to serve as a major science driver for major new radio facilities. However, assuming that the SKA design continues to include long baselines to meet other science drivers, a program for astrometry of nearby stars would be worthwhile for the small marginal cost it would require.

The committee does promote radio astrometry as a powerful tool for science in fields other than exoplanet studies (e.g., Honma et al. 2007; Hirota et al. 2007), and believes it should continue to be supported for those purposes.

Basic Properties of Stars in Support of Exoplanet Science

On page 47, the ExoPTF report states "To optimize the choice of targets and maximize the eventual scientific interpretation of exoplanet observations, it is important to have an ongoing program to measure stellar parameters." The fractional uncertainty in an astrometrically derived exoplanet mass is at best equal to the fractional uncertainty in the host star's mass. Astrometry can contribute to constraining star masses for a range of star types by measuring the orbits of binary stars. Overall, the committee did not place high priority on developing new astrometry programs in this area. Most of the committee found that these quantities are already known well enough across the range of star types comprising the primary targets of a search for Earth-like planets around nearby stars, and improving this knowledge would have a minimal impact on exoplanet science. The merits of stellar astrophysics can be separately evaluated as a science topic on its own, without playing a crucial role in the outcome of the exoplanet projects.

Similarly, the distance to a host star is required to properly characterize it and any astrometrically detected exoplanets. This will be a natural result of any astrometry program and a separate devoted effort is unnecessary. Astrometry may play a role in determining distances to planet host stars with companions detected in other manners, such as radial velocity or transits.

Demonstrating Technology Shared With Future Imaging Missions

Committee members had mixed interest in whether it is important that a space astrometry mission have a role in demonstrating technology that might be shared with a future direct imaging mission (for example, picometer metrology shared with TPF-I).

Space Astrometry Support For Microlensing

As described in Chapter 6, microlensing events are a powerful tool for studying exoplanets around distant stars. The observable being used in current studies is the overall source magnification cause by the gravitational potential of the lensing object(s). The shape of the light-curve provides information about the number of objects in a lensing system, and their relative masses.

Astrometry is a second observable that can provide additional information on the lensing system. During a microlensing event, the apparent position of the source will vary by amounts measurable by the micro-arcsecond astrometry mission.

The committee supports this as an interesting project to pursue if the design of the micro-arcsecond astrometry supports it. However, the mission design should not be altered to specifically address this program, and it should not be allowed to impact negatively the primary mission of detecting Earth-like planets around nearby stars.

Astrometry with a Large-Aperture, Wide-Field Camera in Space

The committee considered a concept for image-plane astrometry using a giant 8-m (or 16-m) space telescope as an alternative for a sub-microarcsecond-capable mission, however it was found to be less capable in terms of astrometric performance. In this concept, the telescope would have a relatively large field of view (FOV) of 2 arcminutes (requiring 16k × 16k pixels for 8 m, 32k × 32k for 16 m). This would represent a reasonable advance in technology over the < 3 arcminute FOV of WFC3 (1k × 1k to 2k × 2k pixels depending on channel) on the > 3× (6×) smaller *HST*. (Note that the 10 degree FOV of *Kepler* is not diffraction limited and not applicable owing to the following considerations; pixelization noise in that case limits astrometric precision, and the detector-related systematic errors are larger as well, while even the 95 Megapixels in the *Kepler* camera is smaller than the 250–1000 Megapixels required for the concept astrometry mission).

If one considers only the photon-noise and diffraction limited SNR of the bright target star, an 8-m (16-m) filled-aperture telescope clearly appears to offer superior performance to a 6-m baseline interferometer—both its angular resolution and collecting area are larger.

However, the real error budget contains many more terms, and in neither the interferometer nor the image plane approach does the photon-noise limited SNR of the bright target star make a significant contribution. Lacking instrumental or systematic noise sources, the dominant term becomes the photon-noise and diffraction-limited SNR of the reference stars.

With smaller individual apertures, the interferometric approach has much larger field of view than even a "wide field camera" on a single giant telescope: in narrow angle mode, a SIM-based architecture uses reference stars distributed over a 2 degree field, compared to the hypothetical 2 arcminute field of a wide field image-plane camera. The area over which the interferometer can select targets is 3600× that of the wide field camera. By far, the brightest reference stars in the field contribute the most SNR to establishing a reference grid, so the number of reference stars on which astrometry is obtained is relatively negligible as long as the brightest few stars, contributing > 50% of the reference light available, are observed. For the much wider-field interferometer, the reference stars can be roughly 3600× brighter. The collecting area for an 8-m (16-m) filled aperture is 350× (1400×) that of the 2 × 30-cm interferometer telescopes; and the resolving power is 1.3× (2.7×) that of the 6-m baseline interferometer. Overall, the interferometer SNR on reference stars (proportional to $F^{1/2} A^{1/2} / R$, for source brightness F, collecting area A, and resolution R) has 2.4× the SNR of the 8-m and 0.6 the SNR of a 16-m wide field camera.

Again, this in not likely to be the dominant term in the error budget of an image plane astrometry camera. Instead, detector systematics are likely to be a dominant error source. Assuming the camera is critically sampled (2 pixels/resolution) the focal plane will have 32,000 × 32,000 pixels, a CCD mosaic. The most precise astrometry with CCD cameras use single CCDs because a single piece of silicon is much more stable over a period of years than a mosaic detector. Developing a mosaic CCD whose dimensional stability over several years is at the 0.1 nm (single atom) level is far beyond current technology. CCD mosaic stability aside, astrometry at the 0.2-µas level implies point spread function (PSF) fitting to within a part in 75,000 (37,500) of the 15 mas (7.5 mas) diffraction limit of the telescope. This is still over two orders of magnitude more precise PSF fitting than typically possible in modern imaging detectors such as those on *HST*. With current technology, the most optimistic estimates of the image-plane astrometry performance is ~50 µas.

Technology obstacles exist requiring a major effort to overcome current PSF fitting limitations in image plane arrays. First is inhomogeneities between detector pixels, and within the pixels themselves, introducing non-uniform responses across a pixel, making fitting below about a hundredth of a pixel impossible with current detectors and calibration methods. New manufacturing processes would be required to make detectors with uniformity 100× better than the current state of the art, and to calibrate that responsivity. Second, the variations in the differential PSF between target and reference must be stable over the timescales of interest (years). These PSF-fitting issues are mitigated in the interferometry case, where the astrometry observable is a differential interferometric delay tied directly to a laser reference, and the same detector pixels are used for target and reference. To be certain, developing the ability to fit to far below the diffraction limit is a challenging proposition; this technology development was possible only through a decade-long effort culminating with the micro-arcsecond metrology (MAM) testbed, detailed in Section 2.2.2. It is not an efficient use of current resources to duplicate this technology development effort for the image-plane astrometry case when the interferometer-based approach is ready for deployment now. This is supported by the fact that even in the limit of systematic errors being less than that of the reference star SNR, the interferometer approach offers roughly equal astrometric precision as the much more expensive 8-m (16-m) filled aperture concept.

While the committee's fundamental conclusion is to support deployment of any form of a sub-micro-arcsecond precision, targeted astrometry mission capable of observing nearby stars, the committee believes the most realistic framework to achieve this is one based on the SIM technology program.

2.2 Observatory Concept.

While many programs for astrometric detection and characterization of exoplanets are supported by the committee, only the design of the highest priority, micro-arcsecond astrometry mission is considered here in depth.

2.2.1 Architecture

The SIM-based architecture is mature and ready for a mission now, and is the most feasible approach to micro-arcsecond astrometry. This architecture may be realized in the form of SIM, SIM-Lite, or Planet Hunter.

A space-based mission is the most promising method of achieving micro-arcsecond level astrometric precisions. Ground based astrometric techniques must look for reference stars within the isoplanatic path, typically ~30 arcsecond. Only a very few of the nearest "best" candidates for an astrometric search for Earth-like exoplanets are double stars. Background field stars in a 30 arcsecond field are typically 18–20 mag. Atmospheric noise and photon noise of the 18 ~ 20 mag reference stars limit any ground based astrometric instrument to > 10 μas in 1 hr of integration. Whereas a ground-based astrometric program will require 100 hours of integration to reach the 1-μas level, a space-based program can reach this level in a 20 minutes. A survey of the most promising 60–100 targets will take ~40% of a 5 year mission, whereas a similar ground based program would take 1500 years!

Field of view considerations favor the SIM architecture over filled-aperture space telescopes for astrometry. SIM uses reference stars up to 1 deg from the target. A space astrometric telescope would have a much smaller field and consequently would have to rely on much fainter reference stars. When the photon noise of the faint reference stars is taken into account SIM's photon limited accuracy is equivalent to a filled aperture 10-m telescope with a ~10 arcmin field of view.

The science instrument considered here is a spatial interferometer, conceptually similar to Albert Michelson's interferometer on the 100-inch telescope at Mt. Wilson in 1913, and to other ground-based amplitude interferometers since that time. It collects two patches of the incoming wavefront from a star, uses a mirror on a movable delay line to apply a suitable time delay to one of the wavefront patches, and combines the patches to form an interference fringe in the pupil plane. The delay is adjusted to give the maximum visibility of the white-light interference fringe packet. The origin of the delay line is defined as its position when the axis of the instrument is perpendicular to the propagation vector of the incoming wavefront, where the axis is the line between the pivot points of the two collecting mirrors at the ends of the instrument. The distance between these pivots is the baseline of the instrument. The angle between the instrument axis and the line of sight to the star is the arccosine of the delay divided by the baseline.

The SIM-based architecture results from twelve years of coordinated technology development and mission design. The architecture consists of one science Michelson stellar interferometer (MSI) capable of micro-arcsecond fringe determination accuracy, a guide star tracking system to determine the attitude of the instrument at the micro-arcsecond level relative to chosen guide stars (about a million times better than a typical spacecraft star tracker), and a metrology system to determine the orientation of the science interferometer baseline relative to the guide star tracking system. Supporting mission elements include: (1) an instrument data system to control the instrument and collect instrument data for return to the ground for processing, (2) a spacecraft bus to provide housekeeping services, (3) a launch vehicle to inject the flight segment into the proper orbit, (4) a mission operations system to monitor and control the flight segment, and (5) a science operations system to plan observations, reduce the science data and distribute science data to the science users.

A number of variants of the SIM-based architecture have been studied by the SIM project team, aimed at providing a full range of science/cost performance options for the science community and NASA to choose from. A brief description of these options follows.

SIM PlanetQuest

This is the most capable of the options, consisting of a 9-m science interferometer baseline and two 7.2-m MSIs to form the guide star tracking system. This mission is launched into an Earth-trailing Solar orbit (ETSO), drifting away from Earth at about 0.1 AU·yr^{-1}. It is launched on one of the largest EELVs (Atlas V 551 or Delta IV Heavy) and tracked by the NASA Deep Space Network (DSN). Mission operations are conducted from JPL and science operations from the NASA Exoplanet Science Institute (NExScI) at Caltech.

SIM-Lite

There are three versions of this option that hit different cost/performance points. All have a 6-m science interferometer baseline, all have one 4.2-m MSI that serves as one of the two guide star trackers, and all have one 30-cm diameter telescope that serves as the second, lower accuracy, guide star tracker. All are launched by an EELV (Atlas V 531 class) into ETSO, are tracked by the DSN, and are operated from JPL and Caltech, the same as the full SIM PlanetQuest. Option variations result from the size of the science interferometer siderostat (50 cm or 30 cm), and the way science operations are carried out.

Planet Hunter

There are two versions of this option with different cost/performance points. Both have one 6-m science baseline that has a restricted field of regard of only 4° (vs. 15° for SIM and SIM-Lite), both have one 4.2-m guide MSI, and both have one 30-cm guide-2 telescope. Options derive from whether the mission is flown in ETSO as for SIM or in a 900 km Sun-synchronous, terminator Low Earth Orbit (LEO). LEO offers a less expensive launch vehicle, less expensive ground communication system (Fairbanks, AL), and the use of magnetic torquers to dump momentum allowing longer mission lifetime but comes at the expense of requiring a large de-orbit engine to clear LEO at the end of mission life and the need to spend more than 50% of mission time maneuvering to avoid Earth-shine entering the instrument.

2.2.2 Performance

The accuracy of an angle measurement is determined by the total number of photo-electrons collected in the interference fringe pattern (mainly set by the brightness of the star, the collecting area, and the integration time), the shape of the pattern (mainly set by the length of the baseline and the wavelength) and knowledge of the baseline vector (direction in 3-space and length).

The relative position of a target star with respect to its group of reference stars is determined during a “visit”. Visits can be either short or long, depending on the measurement accuracy desired. A short visit is about 2200 seconds in length. In a short visit, the target star’s two-dimensional location in the plane of the sky is measured with respect to a local framework defined by the average location of 4 to 5 nearby reference stars. The measurement along each axis takes half of the total, or 1100 s.

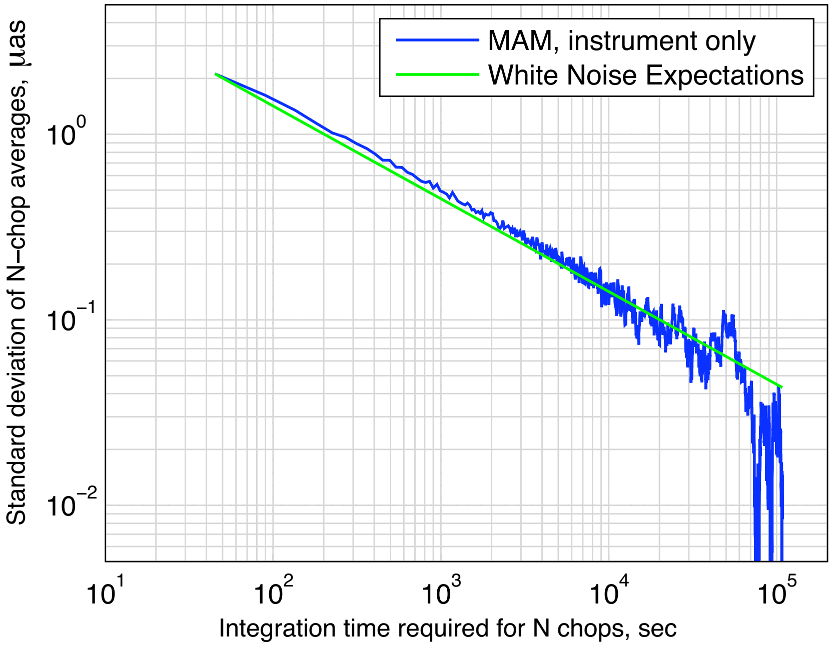

Figure 2-1. Astrometric noise floor demonstrated in the laboratory.

During the 1100 sec time allocated to each axis in a short visit, the angle between the target star and the baseline vector is measured to a "single-star uncertainty" of about 1.0 μas for SIM-Lite and Planet Hunter (and about 0.7 μas for SIM PlanetQuest). Likewise the angle between each of the reference stars and the baseline vector is measured, and the results combined to give the average of the reference stars, to a similar "single-star uncertainty" of about 1.0 μas (or 0.7 μas for SIM PlanetQuest). The angle between the target and reference group is the difference of these angles. The uncertainty is the "differential-measurement accuracy", which is $[(1.0\ \mu as)^2 + (1.0\ \mu as)^2]^{1/2}$ = 1.4 μas along one axis (= 0.98 μas for SIM PlanetQuest).

The key to micro-arcsecond precision lies in the measurement process, which is doubly differential. Differential in angle, over 1 degree, and differential in time over a chop cycle of about 90 s. First-order errors are entirely eliminated.

SIM's laboratory measurements have shown that measurements are photon-noise limited to at least x = 0.035 μas. Up to 1600 (1890) 1.4 μas (1 μas) can be combined with square-root scaling laws remaining valid for SIM-Lite or Planet Hunter (SIM). The noise floor is well below the 0.3 μas signature of an Earth around a Sun-like star at 10pc.

The MAM results were obtained in a test environment substantially worse than that expected for SIM on orbit. Subsystem tests, such as MAM, validate SIM through integrated models that link them. This model linkage was itself defined as a technology milestone and was subjected to rigorous peer review.

The minimum detectable planetary astrometric signature (MDAS) is the instrument noise floor (0.035 μas for SIM-Lite and Planet Hunter, 0.021 μas for SIM PlanetQuest) times the SNR needed (typically ~5.8). This is 0.20 μas for SIM-Lite and Planet Hunter and is 0.12 μas for SIM PlanetQuest.

The minimum detectable Earth-like planet mass is dependent upon the MDAS, stellar distance, stellar mass and the planet's orbit. For a one Solar mass star at 10 pc, the minimum detectable habitable-zone planet mass depends upon where the planet is in the habitable zone. SIM-Lite and Planet Hunter, can detect a 0.44 $M_\oplus$ planet at the outer edge of the habitable-zone (0.29 $M_\oplus$ for SIM PlanetQuest); 0.7 $M_\oplus$ at a 1-AU postion (0.47 $M_\oplus$ for SIM PlanetQuest); and 0.85 $M_\oplus$ at a the inner edge of the habitable zone (0.57 $M_\oplus$ for SIM PlanetQuest).

2.3 Technology

As in the previous section, only technology related to the highest priority, micro-arcsecond astrometry mission is considered here in depth, though several other programs are supported with lower priority.

2.3.1 Past Accomplishments

Background

Although optical and infrared interferometers have been well-developed for ground-based observations (e.g., NPOI, KI, VLTI, CHARA Array, etc.), these facilities are limited by the spatial coherence length, coherence angle, and coherence time imposed by the Earth's atmosphere. Since the early 1990s, the concepts for ground-demonstrated techniques have been developed into space-capable hardware and software with sufficient reliability to enable an unattended five to ten year space-based mission.

Following the success of the Mark III interferometer on Mount Wilson, a program was begun at JPL to identify and develop the necessary technologies to enable space-based interferometry missions. This technology program was later attached to the NASA Origins Program office at JPL and the Space Interferometry Mission.

From 1996 to 2005 a Technical Advisory Committee, chaired by Robert O'Donnell, worked with the technology development team to complete the focused SIM technology development program, and continued with the SIM project to review the transition of the technologies into flight-like hardware. Since 2001, a NASA-Headquarters commissioned Independent Review Team (renamed the External Independent Readiness Board (EIRB)), has monitored technical progress for the mission, and now also continues in this role as the SIM project transitions the technology into flight-like hardware.

Previous Interferometric Astrometry Programs

A number of smaller-scale interferometric astrometry programs have been developed on the ground and in space to demonstrate the technologies and science for a micro-arcsecond astrometry program. Selected efforts are described here.

The Hubble Space Telescope Fine Guidance Sensors (FGS)

While spectacularly successful at locating previously unknown companions to stars, the high-precision radial velocities provided by Doppler spectroscopy only provides a minimum mass, not the actual companion mass. While spectacularly successful at providing parallaxes for thousands of nearby stars, HIPPARCOS could not reliably provide 10% parallaxes for stars more distant than ~100pc. Astrometry with the *Hubble Space Telescope* has provided both.

The many results from the original *HST* FGS astrometry observations include parallaxes of astrophysically interesting stars (Benedict et al. 2000, 2002a, 2002b, 2003; McArthur et al. 1999, 2001), a parallax for the Hyades (van Altena et al. 1997), a link between quasars and the HIPPARCOS reference frame (Hemenway et al. 1997), a determination of low-mass binary star masses (Franz et al. 1998; Benedict et al. 2001), and searches for Jupiter-mass companions to Proxima Cen and Barnard's Star (Benedict et al. 1999). Subsequent FGS work contributed to the study of the lower main sequence mass-luminosity relationship (Henry et al. 1999), the inter-comparison of dwarf novae (Harrison et al. 2004), and parallaxes of cataclysmic variables (Beuermann et al. 2003, 2004; Roelofs et al. 2007) and the Pleiades (Soderblom et al. 2005). Most recently themes have been the cosmic distance scale and extrasolar planetary systems. This includes the galactic Cepheid Period-Luminosity Relationship (PLR) (Benedict et al. 2007) and the determination of extrasolar planetary masses (Benedict et al. 2002c; McArthur et al. 2004; Benedict et al. 2006; Bean et al. 2007).

Regarding the cosmic distance scale, FGS researchers have obtained a parallax for the Pleiades which supports the validity of modern stellar interiors modeling. This work has provided 10% parallaxes for ten Galactic, solar-metallicty Cepheids, resulting in a Period-Luminosity relation that provides distances to the LMC and NGC 4258.

Currently, fewer than 10% of the more than 200 candidate exoplanets orbiting nearby stars have precisely determined masses. Because the most successful technique for detecting candidate exoplanets, the radial velocity method, suffers from a degeneracy between the mass and orbital inclination for most of the known exoplanet candidates, only a minimum mass, M_{sini}, is known. FGS has provided masses for planets in these systems: GJ876, 55 Cnc, Epsilon Eridani, and HD33636.

A preliminary indication is that for the first time the degree of coplanarity of an extrasolar planetary system associated with a normal, main sequence star will be established. Beyond that, *HST* FGS data for similar coplanarity tests on the multiplanet systems associated with HD 128311, HD 202206, μ Ara, and gamma Cep is being collected.

The Palomar Testbed Interferometer (PTI)

Hands-on Training

From 2002–2006 SIM sponsored an interferometry training course for Caltech graduate students and post-docs, and JPL engineers and scientists. This course introduced students to the basics of interferometry theory and practice, and included both six hours of lecture material, and a two-night observing session for students at the Palomar Testbed Interferometer (PTI) (Colavita et al. 1999). The school lectures included both interferometry theory for both interferometric imaging and interferometric astrometry, as well as a description of preparing for observing and reducing/interpreting data. The observing sessions specifically gave students hands-on experience in preparing observing plans, preparing the interferometer for observations (students participated in nightly alignments), and in the reduction of data (e.g. homework assignments including reducing and interpreting data taken the night before).

Demonstration of Dual-star Astrometry

PTI has demonstrated an astrometric precision of < 100 μas between the components of a bright visual binary (Lane et al. 2000). PTI is a long-baseline infrared interferometer at Palomar Observatory developed under NASA funding to demonstrate technology for future ground and space interferometers. The specific experiment mentioned above used PTI in dual-star mode, where the field at each telescope was separated into two narrow fields containing the two components of the bright visual binary 61 Cyg, which were separated in declination by 26 arcsec. The interferometer incorporates two separate interferometer beam trains, including optical delay lines and fringe trackers. Laser metrology is used to measure the delay required to detect fringes, as well as to reference the two beam trains to common fiducials at each telescope.

In the experiment, half the light from one component of the binary was continually tracked by one fringe tracker. The other fringe tracker switched, on a several minute timescale, between the two components of the binary. The key observable was the laser-measured change in delay between the two components, as corrected by residual fringe tracking errors.

The experiment was conducted over a series of 7 nights in 1999. The final results yielded RMS residuals in the measurement of declination of 97 μas, demonstrating the feasibility of high precision narrow-angle astrometry from the ground.

PHASES

The Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) at PTI is a search for giant planets orbiting closely to either star in binary star systems, with astrometric precisions at the 20-μas level for arcsecond-separation binaries. PHASES is motivated both by a desire to study planets in binaries and as an astrometric program developing tools and techniques for SIM.

Seven refereed journal articles have appeared based on PHASES measurements with another in preparation. PHASES science results include reporting the observational limits to planetary companions in a number of target binaries, the precision orbits of binaries and the measured physical properties of the component stars, and characterization of two triple and two quadruple star systems, including establishing the degree of system coplanarity and the physical properties of the stars.

While the 20-μas precision achieved by PHASES represents progress in the field of interferometric astrometry, it should be stressed that the PHASES hardware can only be applied to a very specific class of binary stars and thus represents no competition to the much more versatile micro-arcsecond astrometry mission being promoted for 2010–2020. Technology and analysis efforts are shared between the two, and the micro-arcsecond astrometry mission will benefit from the efforts of the PHASES project.

The Space Interferometry Technology Development Program

In preparation for a micro-arcsecond astrometry mission, a technology program developed and tested components based on the Goal-level performance requirements set by the previous Decadal Surveys: 4 μas wide-angle mission accuracy over the full sky and 1 μas narrow-angle single measurement accuracy over a 1° field of regard. The components were then integrated into subsystem-level testbeds that were used to verify whole branches of the error budget to ensure that there were no missing terms. Finally, system-level testbeds were developed to fully demonstrate that the components functioned as expected in a system with full complexity.

This progressive flow from components, through subsystems, to system-level testbeds occurred for two paths: (1) Real-time optical-path-difference (OPD) nanometer-level control and (2) Picometer-level-knowledge sensing. The nanometer control path verified that vibrations and spacecraft attitude control induced motions could be rejected to a level that allowed acceptable interference fringe visibility (requires better than 10 nm optical path difference stability). The picometer sensing path verified that dynamic displacements of optical elements within the instrument could be measured to a relative precision of a few picometers and absolute distances between elements could be measured to an accuracy of approximately one micron over distances to ten meters.

A complete technology plan focusing on the SIM reference mission was first formally signed by the Origins Program Office in January 1998 and updated in 2003 and signed by NASA Headquarters. Eight (8) key technology developments from this plan were identified as "Technology Gates" with specific objectives, completion dates, and review requirements (TAC and EIRB) as a means for NASA Headquarters to carefully monitor progress. *All 8 Technology Gates have been completed and met their objectives.* These eight gates and their current status are listed in the following table.

Table 2-2. Technology gates of the SIM reference mission.

Technology Gate	Description	Due Date	Complete Date	Performance
1	Next generation metrology beam launcher performance at 100 pm uncompensated cyclic error, 20 pm/mK thermal sensitivity	8/01	8/01	Exceeded objective
2	Achieve 50 dB fringe motion attenutation on STB-3 testbed (demonstrates science star tracking)	12/01	11/01	Exceeded objective
3	Demonstrate MAM Testbed performance of 150 pm over its narrow field of regard	7/02	9/02	Exceeded objective
4	Demonstrate Kite Testbed performance at 50 pm narrow angle, 300 pm wide angle	7/02	10/02	Exceeded objectives
5	Demonstrate MAM Testbed performance at 4000 pm wide angle	2/03	3/03	Exceeded objective
6	Benchmark MAM Testbed performance against narrow angle goal of 24 pm	8/03	9/03	Exceeded objective
7	Benchmark MAM Testbed performance against wide angle goal of 280 pm	2/04, 5/04*	6/04	Met objective
8	Demonstrate SIM instrument performance via testbed anchored predicts against science requirements	4/05	7/05	Met objective

*NASA HQ directed a scope increase (by adding a numerical goal to what had been a benchmark Gate) and provided a 3-month extension when performance fell short

Each of the eight technology Gates developed specific test, modeling, measurement and success criteria that were reviewed by and agreed to with the TAC and EIRB prior to testing. These formed the basis for the post-test evaluation to determine whether or not the test was successful in meeting the objectives of the Technology Gate.

Numerical modeling was a central part of the SIM technology program. Numerical diffraction modeling tools were verified for picometer accuracy over the whole range (near field, mid field and far field) using a testbed specifically developed at Lockheed Martin, Sunnyvale, CA for enabling specific test case comparison to modeling predictions. Opto-mechanical modeling tools were verified at the milli-Kelvin level, again using special testbeds developed at Lockheed Martin, Sunnyvale, CA, and at JPL in Pasadena, CA. These testbed-model comparisons showed excellent agreement (better than a factor of two over the full range of test). This experience, coupled with a similar factor of two or better performance on the subsystem and system level technology testbeds, has provided confidence in the predictive power of the modeling tools used for design and evaluation of the SIM flight system.

Table 2-3. Timeline of SIM engineering milestones.

Engineering Milestone	Description	Due Date	Complete Date	Performance
Formulation Phase				
EM-1	External Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	5/31/06	6/5/06	Exceeded objective
EM-2	Internal Metrology Beam Launcher Brassboard (meet Qual environmental and allocated picometer performance)	4/30/06	5/3/06**	Exceeded objective
EM-3	Metrology Source Assembly Validation (meet Qual environmental and allocated performance)	6/30/06	6/28/06	Exceeded objective
EM-4	Spectral Calibration Development Unit (SCDU) (demo flight-traceable fringe error calibration methodology and validate model of wavelength-dependent measurement errors)	8/30/07	12/10/07	Met objectives
EM-5	Instrument Communication H/W & S/W Architecture Demo (validate SIM's multi-processor communications system using two brassboard instrument flight computers, ring bus, and flight software version 2.0 with specific S/W functions as listed)	4/1/07	3/5/07	Met objectives
Implementation Phase				
EM-6	Engineering Models for Metrology Fiducials (double and triple corner cubes fully meeting SIM flight requirements)	9/30/07*	Implementation phase Milestones deferred indefinately along with mission	
EM-7	Metrology Source Engineering Models (optical bench; fiber splitters; fiber switches; fiber distribution assembly; laser pump module: all fully meeting SIM flight performance requirements per table)	9/30/08*		
EM-8	Instrument/Mission Performance Prediction (update Tech Gate #8 using latest hardware results)	9/30/08*		
EM-9	Integration of S/C FSW build-1 with phase-1 of the S/C engineering model testbed (demonstrates specific S/W functions)	10/1/08*		

*Completion dates deferred indefinately due to FY07 NASA decision to delay SIM indefinitely

** Actual signoff by NASA HQ delayed unil 12/12/06 due to requests for additional thermal testing by the TAC and EIRB boards

Another outcome of the modeling effort was the verification of the full SIM error budget, which showed consistency of the interplay between the terms in the error budget and, perhaps as importantly, showed that there were no missing terms in the error budgets (which would have shown up as un-modeled errors in the subsystem and system testbeds). This is very important in reducing the risk that there will be fundamental surprises during the flight system design, development, test and operations.

The technology program was completed in July 2005 and the final closeout report was signed by NASA Headquarters in March 2006 after extensive review and discussion with the TAC and EIRB. Detailed discussion of the SIM technology program can be found in recent SPIE and IAC papers by Laskin.

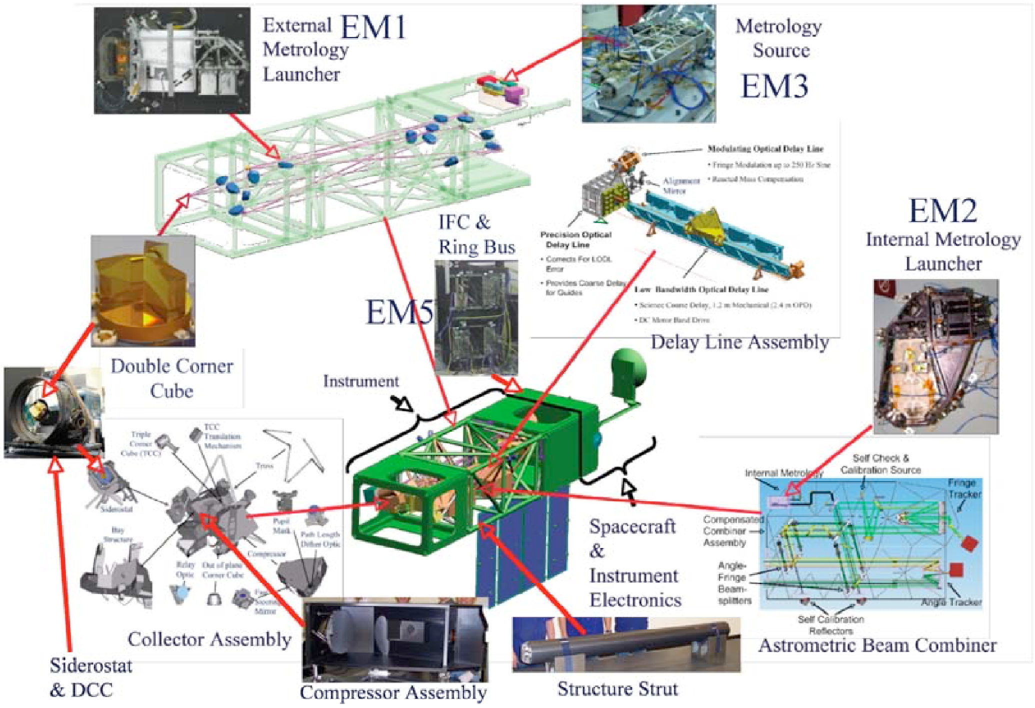

Figure 2-2. The relationship between SIM engineering milestones.

Engineering Milestones

SIM continues to transition technology to flight-qualifiable hardware through a series of engineering milestones aimed at building flight-like hardware that is environmentally tested (when required) and performance tested to verify its capability to perform to flight requirement allocations. These flight-like hardware assemblies are called brassboards and demonstrate that flight hardware for the SIM mission can be built. Each Engineering Milestone is subject to the same TAC/EIRB establishment of test and success criteria prior to testing and subject, post testing, to detailed review by the TAC/EIRB against these success criteria, following exactly the same process as was used for the technology program.

The nine Engineering Milestones that were established for SIM are presented in Table 2-3, showing the five that will be completed during the Formulation Phase (Phase A/B) and the four that would be completed during the Implementation Phase (Phase C/D/E) prior to the Critical Design Review (CDR). Of the Formulation Phase EMs, all five have been successfully completed.

Many components have been engineered to flight-ready status. These are summarized in the following figure:

Double-Blind Test of Planet Finding Capability

At first glance, it should not be difficult to extract the astrometric signal of an Earth-like planet from the composite signal of a system of planets around a star, because each planet has its own frequency in time, so in a Fourier analysis of the total signal, the signature of any given planet should stand out compared to any other planet. However in reality the case might be not so simple, because, for example, a planet in an eccentric orbit with a dominating signal (e.g., a Jupiter) might have harmonic terms that are not recognized as such but might look like a separate planet, or a long-period planet observed over a time shorter than that period would have noise generated at many frequencies owing to the difficulty of distinguishing a proper motion on the sky from a part of an orbit. For these reasons, plus the fact that a mission should always be simulated before it is flown, we initiated a double-blind simulation to see how well Earth-like planets (i.e., terrestrial masses, habitable-zone periods) in multi-planet systems could be detected with SIM-Lite, with the help of RV measurements. An additional goal was to see what measurement accuracy of SIM-Lite is necessary to achieve a goal of being able to detect Earth-like planets.

The simulation was organized with four teams of scientists, the planet modelers (Team A), the data simulators (Team B), the data analyzers (Team C), and the overall summarizers (Team D). An independent review/reporting team and a NASA appointed External Independent Readiness Board participated to oversee the entire process and advise NASA.

If the reliability of detections is taken to be the ratio of correct detections to the total of correct plus false alarms, then the reliability ranged from about 40% to 100%, with 3 groups being over 80% (one group was not able to finish the exercise on time). In principle, this value should have been about 99%, if the false alarm rate had truly been 1%. However the short amount of time for the exercise meant that only one group had enough experience to fully weed out false alarms. For this reason the exercise is being repeated with extra statistical tests added.

The accuracy of results also was close to the theoretically expected value, for the key parameters of period and mass. We calculated the expected accuracy using a minimum-variance bound method (Gould, 2008). Comparing the subjectively correct answers to the actual answers, and scaling that offset by the expected value of the offset, we found a roughly Gaussian distribution, with approximately the expected number (68%) of values lying in the range (−1, +1), no significant offset from zero (i.e., no bias), and very few values in the range between plus or minus 1 and 3. However beyond the 3-σ point, where essentially no points should fall, we found a handful of cases (14%), and these appear to be situations where the expected error was very small (say less than 1% in mass or period), and the actual error was more than 3 times that value, in other words a good measurement but not as perfect as theoretically expected.

In overall summary, this first phase of the simulation showed that the answers to our initial questions are (1) yes, Earths can be detected in multi-planet systems, and (2) the sensitivity needed is almost exactly the posited situation of a 5-year SIM-Lite mission, using 40% of the available observing time, with the expected noise level and a 6-m baseline, plus the additional help (mostly with long-period planets) from 15 years of RV observations. This first phase of study is being followed up with phase 2 in which all tentative detections will be subject to an additional statistical F-test and a stability test, as well as additional time for the analysis, before being declared as detections. In conclusion, we note that the exercise generated great enthusiasm among the participants, each of whom put in an enormous amount of personal time to find the planets, and we learned a number of useful lessons along the way.

2.3.2 Future Milestones

With well over $100M invested in the development of this technology, remaining risks for a user of this technology are the usual ones that occur during the implementation of any large system (manufacturing errors, interface mismatches, etc.).

Completion of Engineering Milestones 6–9

The remaining Engineering Milestones will be completed as the mission moves into its implementation phase.

Developing Hardware and Software into Flight Qualifiable Components

Engineering development continues for turning the demonstrated components into flight qualifiable hardware and software. This effort has shown that, even for the most sensitive picometer-hardware, these components can be built using conventional flight hardware fabrication techniques with no degradation in performance from that of the technology demonstrations.

Flight Software Development

Technology testbeds developed for SIM have demonstrated all key algorithms for control and measurement of the instrument. The fifth engineering milestone demonstrated a distributed computing environment that supports the strict timing requirements for high-bandwidth control of hardware that is distributed over a very large structure (for example, SIM or TPF-I). Processing of the SIM testbed measurements have taught the team how to process the instrument output to achieve the required measurement accuracy and precision in ways not anticipated early in the technology program, significantly relaxing hardware requirements. These data-processing lessons-learned should form the basis for ground processing for any flight interferometer.

Combining Science Payload and Spacecraft

Interactions between the spacecraft bus and the instrument are also well understood. These interactions include: vibration suppression (simple two-stage passive vibration isolation is sufficient), attitude stabilization for beam walk suppression (using the two guide interferometers as a micro-arcsecond two-axis star tracker to control the spacecraft attitude control system; about 10^6 times more accurate than a typical spacecraft star tracker), and torque feed-forward from the instrument to the spacecraft attitude control system to minimize attitude disturbances resulting from the motion of instrument siderostats and delay lines.

Analysis of SIM-Lite’s Astrometric Capabilities

A Request for Proposals (RFP) has been made for ~20 separate studies for what can be accomplished with SIM-Lite’s astrometric capability, some of which are expected to address planet finding capability. The RFP can be found on the MSC.caltech.edu web site. Proposals were due June 13, 2008 and will result in one-year contract awards.

Completion of the Planet Hunter Strategic Mission Concept

A "Planet Hunter" Advanced Strategic Mission Concept Study is currently underway that will be complete by March 2009. This study will include independent cost estimates of the Planet Hunter mission concept.

Selection of Mission Concept to be Deployed

SIM-based concepts are expected to be reviewed by the upcoming Astrophysics Decadal Survey. Planet Hunter and a version of SIM-Lite are expected to be presented for review.

2.4 Research & Analysis Goals

2.4.1 R&A in 2010–2020

The top science goals for astrometry related to exoplanet science in the 2010–2020 decade are:

- Detect Earth-like planets in the habitable zones of nearby stars.
- Characterize Earth-like planets in the habitable zones of nearby stars, including important physical quantities such as mass.
- Characterize the orbits of Earth-like planets in the habitable zones of nearby stars, in preparation of a direct imaging mission, to make direct imaging more efficient.
- Characterize exoplanet systems with multiple planets, including planet-planet interactions and orbital coplanarities, quantities important in understanding the formation and evolution of planetary systems.

All are addressed by an astrometric mission capable of single-measurement precisions on the scale of a micro-arcsecond or better. The committee finds the best way to achieve these goals is to deploy a space-based astrometry mission based on the SIM architecture, in the early part of the decade.

Previous decades have been spent analyzing the mission design for a micro-arcsecond astrometry mission. This coming decade should be spent operating such a program and analyzing the science products it returns.

The astrometry committee recommends a timeline that will obtain enough results from a micro-arcsecond astrometry mission by the end of the decade for analyzing results impacting the design of future direct imaging programs.

The astrometry committee strongly supports the non-exoplanet science programs such a mission would enable.

No science analysis effort is complete without the support of dedicated theorists. The astrometry committee recommends supporting theoretical efforts in planet formation, dynamics, and conditions for habitability.

2.4.2 Astrometry Beyond 2020

On page 28, the ExoPTF report finds that for the 11–15 year (2019–2023) timeframe "Assuming the space-borne astrometric mission described above is fielded in the second time epoch, no additional major space-based astrometric effort is envisioned in this time frame." The committee agrees with this conclusion.

Beyond the currently envisioned micro-arcsecond class astrometry mission, what roles might astrometry play in the field of exoplanets? First, longer-term monitoring of stars can capitalize on astrometry's increasing sensitivity with planet period. A many-decade survey from ground or space, such as that being initiated at the VLTI with PRIMA, will contribute to the understanding of outer planets around other stars. Second, one can consider the fundamental astrophysical limits to the astrometric technique, given an otherwise perfect instrument. A summary evaluation in comparison to the radial velocity technique is given as follows (Catanzarite et al. 2008), in regards to sensitivity to low-mass planets.

From studies of our own star, as well as nearby F, G, and K dwarfs, we expect the flux of solar-type stars to vary in a complex way over many timescales. Intensive study of the Sun's flux variability from space over that past few decades has revealed that it is (down to hourly timescales) mostly accounted for by magnetic surface features such as sunspots (dark regions) and faculae (bright regions). The evolution of sunspots and faculae introduce jitter into the Sun's centroid and radial velocity. Typical sunspot group lifetimes are about 10 days; within this coherence time, the jitter is systematic and cannot be averaged down by multiple measurements. Sunspot jitter can be considered as 'noise' in astrometric and RV measurements, and can be quantified. Using a dynamic sunspot model to match the Sun's flux variability it is found that the intrinsic jitter of the Sun's centroid is about 0.7 micro-AU per measurement for a signal with a period near one year (such as Earth in a 1-AU orbit), and the radial velocity jitter is about 0.6 m s^{-1} per measurement.

The astrometric jitter in a measurement of the Sun's angular wobble depends on distance; at 10 pc it is ~0.07 μas. With 100 measurements spaced farther apart than the coherence time, the jitter averages down to 0.007 μas, a factor of 5 *below* the instrumental systematic noise floor of 0.035 μas, and 40 times lower than the signature of Earth. Thus starspots, expected to be the major astrophysical contribution to noise in astrometric measurements of stars, do not pose a significant problem for detection of habitable planets around solar-type stars. On the other hand radial velocity jitter noise due to sunspots is about 7 times *higher* than the Earth's RV signal. A good detection of Earth requires averaging down the noise to 6 times *lower* than the RV signal. So sunspot jitter imposes a severe limit on the capability of the RV method to detect Earth around a star like the Sun. Even in the absence of other astrophysical and instrumental effects, it would take 35 years (1800 measurements spaced apart by more than a week) to detect Earth via RV. But stellar pulsations and granulation also introduce RV jitter in measurements of solar-type stars. The intrinsic astrophysical noise floor for RV measurements due to all of these processes is thought to be at least 1 m s^{-1}. In the long-term, efforts to improve the astrometric precisions of focal plane arrays may make future giant space telescopes useful for precision astrometry.

2.5 Contributors

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2.6 References

Bean, J. L. et al. 2007, "The Mass of the Candidate Exoplanet Companion to HD 33636 from Hubble Space Telescope Astrometry and High-Precision Radial Velocities," AJ, 134, 749

Benedict, G. F. et al. 1999, "Interferometric Astrometry of Proxima Centauri and Barnard's Star Using HST Fine Guidance Sensor 3: Detection Limits for Substellar Companions," AJ, 118, 1086

Benedict, G. F. et al. 2000, "Interferometric Astrometry of the Detached White Dwarf-M Dwarf Binary Feige 24 Using HST Fine Guidance Sensor 3: White Dwarf Radius and Component Mass Estimates," AJ, 119, 2382

Benedict, G. F. et al. 2001, "Precise Masses for Wolf 1062 AB from Hubble Space Telescope Interferometric Astrometry and McDonald Observatory Radial Velocities," AJ, 121, 1607

Benedict, G. F. et al. 2002a, "Astrometry with the Hubble Space Telescope: A Parallax of the Fundamental Distance Calibrator RR Lyrae," AJ, 123, 473

Benedict, G. F., et al. 2002b, "Astrometry with the Hubble Space Telescope: A Parallax of the Fundamental Distance Calibrator δ Cephei 2002b," AJ, 124, 1695 (2002b)

Benedict, G. F., et al. 2002c, "A Mass for the Extrasolar Planet Gliese 876b Determined from Hubble Space Telescope Fine Guidance Sensor 3 Astrometry and High-Precision Radial Velocities," ApJL, 581, L115

Benedict, G. F., et al. 2006, "The Extrasolar Planet ε Eridani b: Orbit and Mass," AJ, 132, 2206

Benedict, G. F., et al. 2007, "Hubble Space Telescope Fine Guidance Sensor Parallaxes of Galactic Cepheid Variable Stars: Period-Luminosity Relations," AJ, 133, 1810

Beuermann, K. et al. 2003, "A precise HST parallax of the cataclysmic variable EX Hydrae, its system parameters, and accretion rate," A&A, 412, 821

Beuermann, K. et al. 2004, "An HST parallax of the distant cataclysmic variable V1223 Sgr, its system parameters, and accretion," A&A, 419, 291

Cameron, B., Britton, M. & Kulkarni, S., 2008, "Precision Astrometry with Adaptive Optics," [arXiv:0805.2153]

Catanzarite, J., Law N., & Shao, M., 2008, "Astrometric Detection of exo-Earths in the Presence of Stellar Noise," Proc. SPIE, 7031-91

Cumming, A., Butler, R. P., Marcy, G. W., Vogt, S. S., Wright, J. T., & Fischer, D. A., 2008, "The Keck Planet Search: Detectability and the Minimum Mass and Orbital Period Distribution of Extrasolar Planets," PASP, 120, 531–554

Franz, O. G. et al. 1998, "The First Definitive Binary Orbit Determined with the Hubble Space Telescope Fine Guidance Sensors: Wolf 1062 (Gliese 748)," AJ, 116, 1432

Goullioud, R., Catanzarite, J. H., Dekens, F. G., Shao, M., & Marr, J. C. IV 2008, "Overview of the SIM PlanetQuest Light mission concept," Proc. SPIE, 7013, 70134T

Hirota, T., et al. 2007, "Distance to Orion KL Measured with VERA," PASJ, 59, 897

Honma, M. et al. 2007, "Astrometry of Galactic Star-Forming Region Sharpless 269 with VERA: Parallax Measurements and Constraint on Outer Rotation Curve," PASJ, 59, 889

Ida, S. & Lin, D.N.C. 2004a, "Toward a Deterministic Model of Planetary Formation. I. A Desert in the Mass and Semimajor Axis Distributions of Extrasolar Planets," ApJ, 604, 388–413

Ida, S. & Lin, D.N.C. 2004b, "Toward a Deterministic Model of Planetary Formation. II. The Formation and Retention of Gas Giant Planets around Stars with a Range of Metallicities," ApJ, 616, 567–572

Ida, S. & Lin, D.N.C. 2005, "Toward a Deterministic Model of Planetary Formation. III. Mass Distribution of Short-Period Planets around Stars of Various Masses," ApJ, 626, 1045–1060

Lane, B., et al. 2000, "Direct detection of pulsations of the Cepheid star ζ Gem and an independent calibration of the period-luminosity relation," Nature, 407, 485

Laskin, R. A. 2006, "Successful completion of SIM-PlanetQuest technology," Proc. SPIE, 6268, 626823

Laskin, R. A. 2006, "SIM-PlanetQuest technology completion: A retrospective view," International Astronautical Congress, Valencia, Spain, IAC-06-A3.P.1.05

Marr, J. C. IV, Shao, M., & Goullioud, R. 2008, "SIM-Lite: Progress report," Proc. SPIE, 7013, 70132M

Mayor, M. & Queloz, D. 1995, "A Jupiter-Mass Companion to a Solar-Type Star," Nature, 378, 355

McArthur, B. E. et al. 1999, "Astrometry with Hubble Space Telescope Fine Guidance Sensor 3: The Parallax of the Cataclysmic Variable RW Triangulum," ApJL, 520, L59

McArthur, B. E. et al. 2001, "Interferometric Astrometry with Hubble Space Telescope Fine Guidance Sensor 3: The Parallax of the Cataclysmic Variable TV Columbae," ApJ, 560, 907

McArthur, B. E., et al. 2004, "Detection of a Neptune-Mass Planet in the ρ^1 Cancri System Using the Hobby-Eberly Telescope," ApJL, 614, L81

Pravdo, S.H., Shaklan, S.B., Henry, T., Benedict, G.F. 2004, "Astrometric Discovery of GJ 164B," ApJ, 617, 1323

Pravdo, S.H., Shaklan, S.B., & Lloyd, J.P. 2005, "Astrometric Discovery of GJ 802b: In the Brown Dwarf Oasis?" ApJ, 630, 528

Pravdo, S., Shaklan, S., Redding, D., Serabyn, E., & Mennesson, B. 2007, "Finding Exoplanets around Old and Young Low-Mass Stars," whitepaper submitted to the AAAC Exoplanet Taskforce

Pravdo, S. H.., Shaklan, S.B., Wiktorowicz, S.J., Kulkarni, S., Lloyd, J.P., Martinache, F., Tuthill, P.G., & Ireland, M.J. 2006, "Masses of Astrometrically Discovered and Imaged Binaries: G78-28AB and GJ 231.1BC," ApJ, 649, 389

Raymond, S. N., Mandell, A. M., & Sigurdsson, S. 2006, "Exotic Earths: Forming Habitable Worlds with Giant Planet Migration," Science, 313, 1413–1416

Roelofs, G. H. et al. 2007, "A. Hubble Space Telescope Parallaxes of AM CVn Stars and Astrophysical Consequences," ApJ, 666, 1174

Scargle, S. D. 1982, "Studies in astronomical time series analysis. II - Statistical aspects of spectral analysis of unevenly spaced data," ApJ, 263, 835

Schaefer, B. E. 2007, "A Problem with the Clustering of Recent Measures of the Distance to the Large Magellanic Cloud," ArXiv e-prints, 709, arXiv:0709.4531

Soderblom, D. R. et al. 2005, "Confirmation of Errors in Hipparcos Parallaxes from Hubble Space Telescope Fine Guidance Sensor Astrometry of the Pleiades," AJ, 129, 1616

Tarter, et al. 2007, "On the Habitability of Planets Around Red Dwarf Stars," Astrobiology, 7, 30–65

Unwin, S., et al. 2008, "Taking the Measure of the Universe: Precision Astrometry with SIM PlanetQuest", PASP, 120, 38

Wetherill, G. W. 1996, "The Formation and Habitability of Extra-Solar Planets," Icarus, 119, 219–238