SIM PLANETQUEST SCIENCE & TECHNOLOGY: A STATUS REPORT

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ABSTRACT

Optical interferometry will open new vistas for astronomy over the next decade. The Space Interferometry Mission (SIM-PlanetQuest), operating unfettered by the Earth's atmosphere, will offer unprecedented astrometric precision that promises the discovery of Earth-analog extra-solar planets as well as a wealth of important astrophysics. Results from SIM will permit the determination of stellar masses to accuracies of 2% or better for objects ranging from brown dwarfs through main sequence stars to evolved white dwarfs, neutron stars, and black holes. Studies of star clusters will yield age determinations and internal dynamics. Microlensing measurements will present the mass spectrum of the Milky Way internal to the Sun while proper motion surveys will show the Sun's orbital radius and speed. Studies of the Galaxy's halo component and companion dwarf galaxies permit the determination of the Milky Way's mass distribution, including its Dark Matter component and the mass distribution and Dark Matter component of the Local Group. Cosmology benefits from precision (1-2%) determination of distances to Cepheid and RR Lyrae standard candles. The emission mechanism of supermassive black holes will be investigated. Finally, radio and optical celestial reference frames will be tied together by an improvement of two orders of magnitude.

Optical interferometers present severe technological challenges. The Jet Propulsion Laboratory, with the support of Lockheed Martin Advanced Technology Center (LM ATC) and Northrop Grumman Space Technology (NGST), has addressed these challenges with a technology development program that is now complete. The requirements for SIM have been satisfied, based on outside peer review, using a series of laboratory tests and appropriate computer simulations: laser metrology systems perform with 10 picometer precision; mechanical vibrations have been controlled to nanometers, demonstrating orders of magnitude disturbance rejection; and knowledge of component positions throughout the whole test assembly has been demonstrated to the required picometer level. Technology transfer to the SIM flight team is now well along.

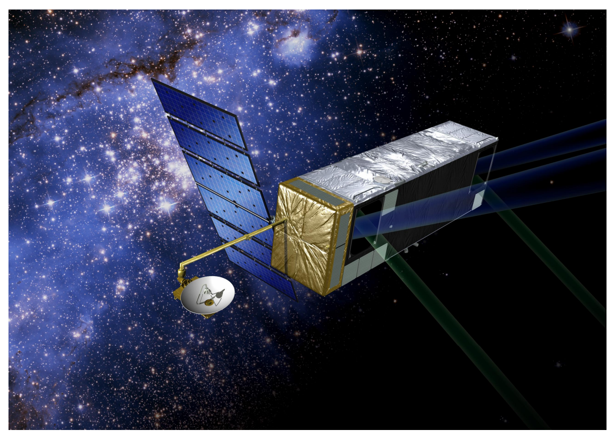

Fig. 1: Artist's conception of SIM

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1. INTRODUCTION

SIM PlanetQuest (Figure 1) will exploit the classical measuring tool of astrometry with unprecedented precision to make dramatic advances in many areas of astronomy and astrophysics. SIM directly serves NASA's goal of searching for habitable planets, as directed by the U.S. President's Vision for U.S. Space Exploration[1]: *Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars.* SIM can survey the "best" 69 stars for planets with masses of less than one earth-mass or more to identify potential Earth analogs and determine their masses and orbital properties. SIM will also survey a few thousand stars of a much wider variety of ages, spectral types, and

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other properties to build up a complete understanding of the formation, evolution, and architecture of planetary systems generally. The 2000 AASC report[2] explicitly called for scientific capabilities ". . . [enabling] the *discovery of planets much more similar to Earth in mass and orbit* than those detectable now, and . . . [permitting] astronomers to *survey the Milky Way Galaxy 1,000 times more accurately* than is possible now." SIM meets both these directives.

The scientific return from SIM will also include improving our understanding of the physical properties of stars, determining the mass and its distribution in our Galaxy, observing the motions of the Milky Way's companions in the Local Group, and probing the behavior of supermassive black holes in other galaxies. More than half of the assigned SIM time has been allocated to astrophysics questions. A substantial share of time remains open for future assignment. It is the sum total of these and other scientific capabilities that led the 1990 [3] and 2000 National Research Council (NRC) Decadal Reports ([2] and [4]) to endorse SIM as an important part of the United States' program in astronomy and astrophysics including: "…*trigonometric determination of distances throughout the galaxy*, and the study of the *mass distributions of nearby galaxies from stellar orbits*." At the request of the NASA Associate Administrator for Space Science, in 2002 the NAS Committee on Astronomy and Astrophysics provided an updated assessment on SIM which re-affirmed this conclusion.

In both astrophysics and planet-finding, SIM is certain to provide new discoveries, refine astrophysical quantities, and re-write textbooks. SIM observations provide fundamental astrophysical information which is needed by other missions, including Kepler, GAIA, James Webb Space Telescope (JWST), and Terrestrial Planet Finder (TPF). The synergy between SIM and these missions is discussed later.

2. SCIENCE INVESTIGATIONS

Planet Searches

The SIM Young Stars and Planets Project (Charles A. Beichman, P. I.) will investigate the frequency of giant planet formation and the early dynamical history of young stars. Its goal is to understand how the diverse architectures of our own and other planetary systems had their origins in the formation processes of cloud collapse, disk formation and accretion, planet formation and migration, and disk dispersal. By detecting Jupiter-mass planets orbiting young stars in the critical orbital range of 1 to 5 AU, this investigation will develop a dataset for comparison with the planetary systems found around mature stars discovered with other SIM Key Projects, and with planets in distant orbits (50-100 AU) found around young stars (<10 Myr) through AO imaging.

The bulk of this program is a planet search around 200 of the nearest (<150 parsecs [pc]) and youngest (0.5-100 Myr) solar-type stars. Only astrometry with SIM can find these planets because a) photospheric oscillations limit radial velocity measurements to ~100 times worse sensitivity than for mature stars; and b) the great distance to these stars (25-150 pc) makes direct imaging of any inner solar system (<5AU or 30 milliarcsec at Taurus) impossible even for advanced Adaptive Optics systems.

Among the questions addressed are:

- *What is the incidence of gas giant planets around young, solar-mass stars in the orbital range 1 AU to 5 AU? When and where do gas giant planets form?*
- *What is the origin of the apparent dearth of companion objects between planets and brown dwarfs seen in mature stars?*

In a second part of this program, SIM will measure distances and orbital properties of ~100 stars precisely enough to determine the masses of single and binary stars to an accuracy of 1%. This information is required to calibrate the pre-main sequence tracks that serve as a chronometer ordering the events that occur during the evolution of young stars and planetary systems.

The SIM key project Extrasolar Planet Interferometric Survey (EPIcS) (Michael Shao, P. I.) is a novel two-tiered SIM survey of nearby stars that exploits the capabilities of SIM to achieve two scientific objectives: (i) to identify Earth-like planets in habitable regions around nearby Sun-like stars; and (ii) to explore the nature and evolution of planetary systems in their full variety.

The Tier 1 survey is designed primarily to address the first objective, the detection of Earth-like planets around nearby stars. The Tier 2 targets will consist of ~2100 stars from the following diverse classes: all main sequence spectral types, in particular early types; binary stars; stars with a broad range of age and metallicity; stars with dust disks; evolved stars; white dwarfs; and stars with planets discovered by radial-velocity surveys. Each class addresses specific features of the planet-formation process (*Are metals necessary for giant planet formation? Does the number of planets decline slowly with time due to dynamical evolution? What is the relation between dust disks and planets?*), and will contain >100 targets to ensure that the findings are statistically robust.

The SIM key project Discovery of Planetary Systems with SIM (Geoffrey W. Marcy, P. I.) team has the following goals:

1. Detect terrestrial planets of 1 – 3 M_{Earth} around stars closer than 8 pc.
2. Detect 3 – 20 M_{Earth} planets around stars at a distance of 8 – 30 pc.
3. Determine absolute masses of planets previously detected with radial velocity studies and search for additional planets
4. Determine the degree of co-planarity in known multiple systems
5. Reconnaissance for the Terrestrial Planet Finder (TPF)

This investigation seeks to determine:

- The occurrence rate and mass distribution of terrestrial planets
- The architecture of planetary systems
- Eccentricities of the orbits of low-mass planets
- The occupancy rate of the habitable zone

and ask

What fraction of stars have planetary systems?
How many planets are there in a typical system?
What is their distribution of masses and orbital semi-major axes?
How common are circular orbits?
How commonly do planetary systems have architecture similar to that of our Solar System?

Recent work showing the capabilities of SIM for finding earth-mass planets in habitable zones is found in Catanzarite et al.[5] and in Table 1 and Figs. 2 and 3. SIM will explore volumes of the discovery space unavailable to other methods and projects.

Table 1. SIM Habitable Planet Survey

Mass sensitivity at mid-habitable zone	1 $M_\oplus$	2 $M_\oplus$	3 $M_\oplus$
# of target stars that can be surveyed (1)	69	160	259
# of target stars that can be surveyed (2)	101	233	360

(1) Surveys with mass sensitivities of 1, 2, or 3$M_\oplus$ using 40% of SIM mission time (five years).
(2) Surveys with mass sensitivities of 1, 2, or 3$M_\oplus$ using 75% of SIM mission time (the maximum available for science investigations over five years).

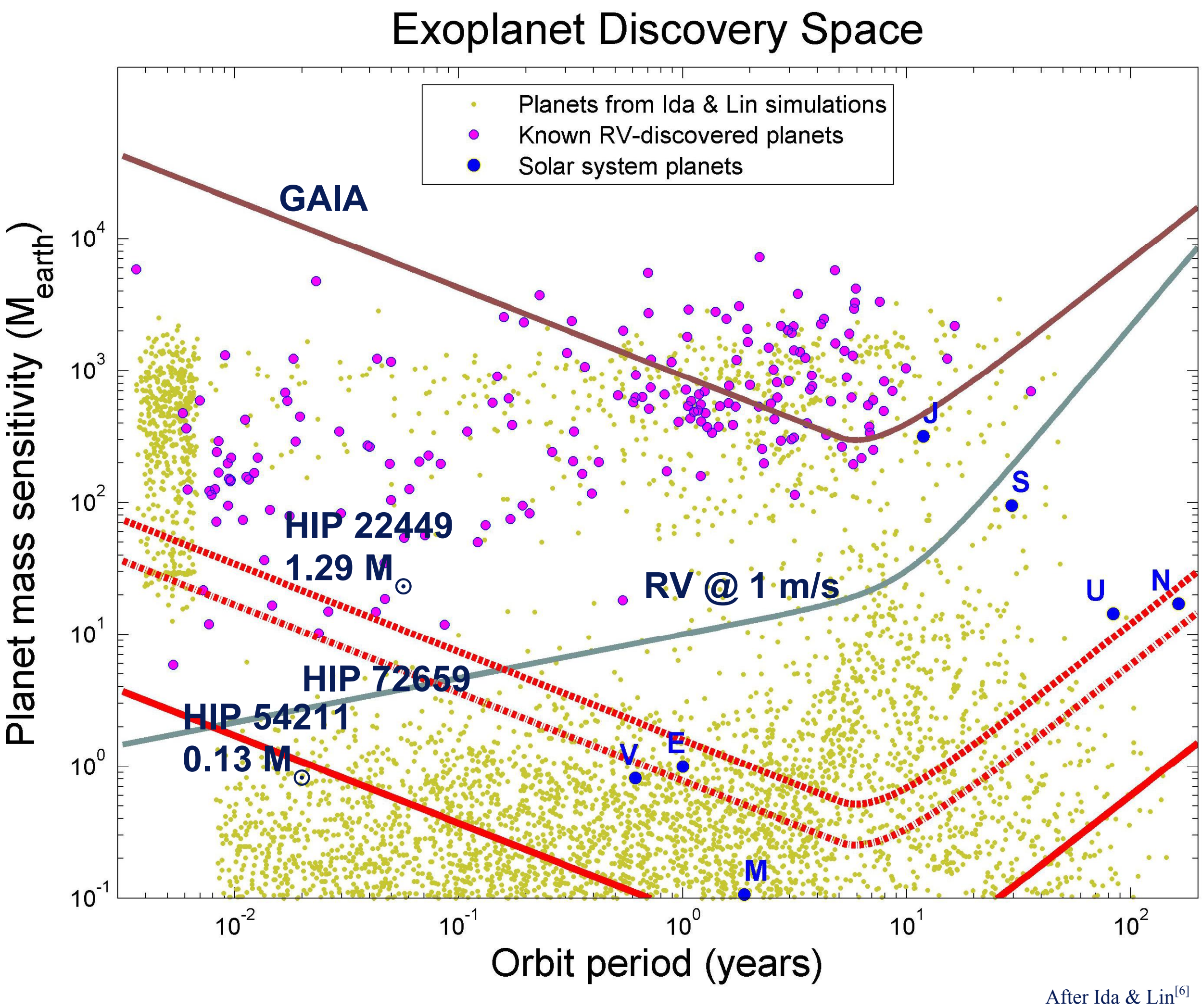

Fig. 2: The planet discovery potential for groundbased and space mission searches – SIM's Earth Analog Survey. RV stands for ground based radial velocity measurements. SIM will find and determine orbits of terrestrial planets other methods cannot. Red curves: best, median, and worst of 69 Earth Analog Survey targets for SIM, labeled by HIPPARCOS catalog number. Unwin *et al.* [7] discuss this figure in detail.

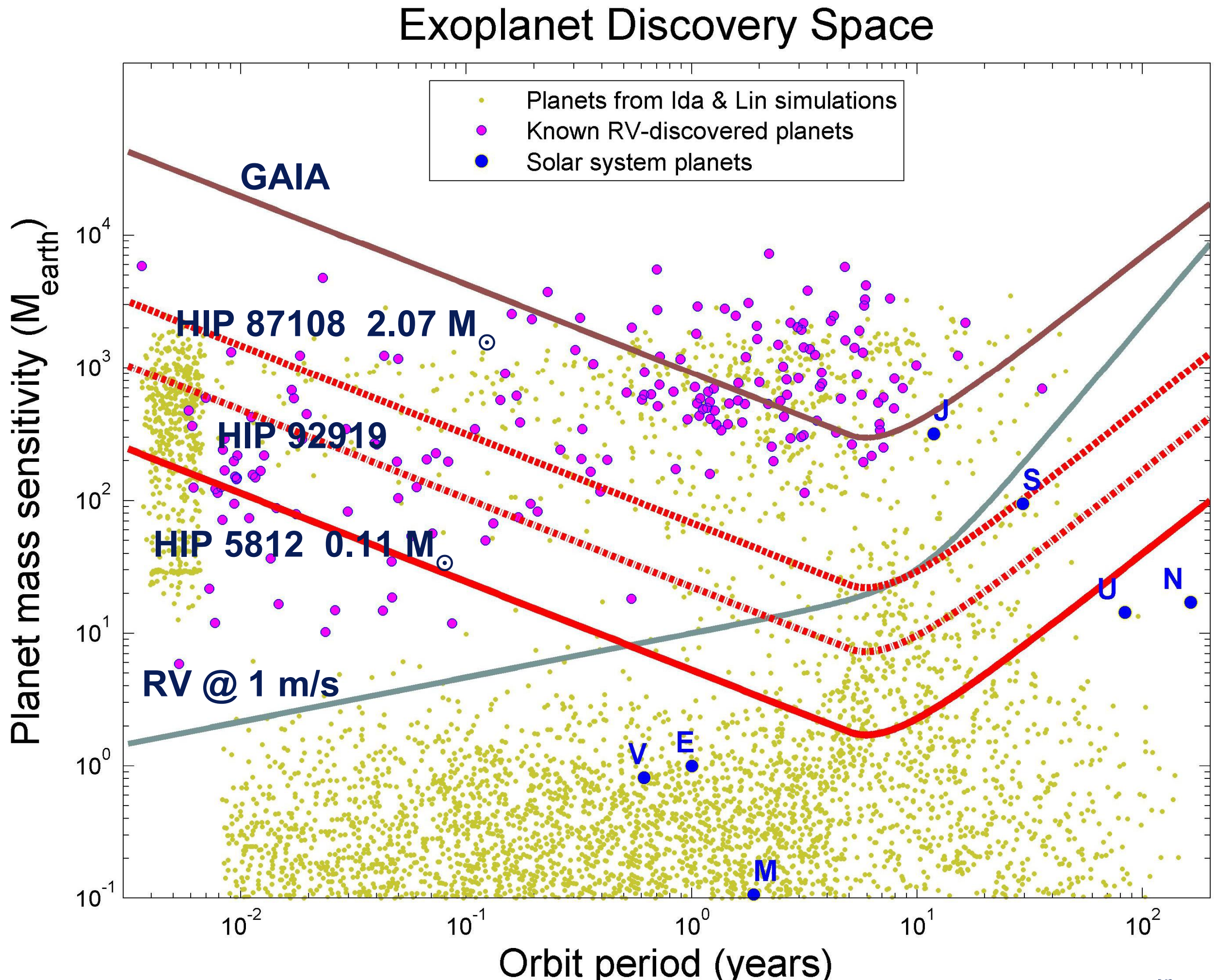

Fig. 3: The planet discovery potential for ground based and space mission searches – SIM's Broad Survey. RV stands for ground based radial velocity measurements. SIM will find and determine orbits of terrestrial planets other methods cannot. Red curves: best, median, and worst of 2100 Broad Survey targets, labeled by HIPPARCOS catalog number. Unwin *et al*.[7] discuss this figure in detail.

Synergy of SIM and Other Missions

In this Section we discuss the scientific connections and synergy between SIM and four specific future missions, Kepler, GAIA, JWST, and TPF. This topic has also been addressed in Traub et al.[8] and Beichman et al.[9].

COROT, Kepler and SIM will provide the many order-of-magnitude improvements in sensitivity and resolution (Figure 2) relative to groundbased efforts needed to detect other Earths in the habitable zones of their parent stars using indirect techniques of transits, radial velocity, and astrometry. Once we have detected these planets via indirect means, we will need a number of missions to characterize these planets physically and to search for evidence of life in any atmospheres these planets may possess.

The combination of transit photometry with COROT and Kepler, follow-up spectrophotometry from JWST, and follow-up radial velocity data give unique information on planetary mass, radius, density, orbital location, and, in favorable cases, composition of the upper atmosphere. These data, available for large numbers of planets, will revolutionize our understanding of gas-giant and icy-planets. While less information will be available for smaller, rocky planets, a critical result of the transit surveys will be the frequency of Earth-sized planets in the habitable zone.

We will ultimately require three complementary datasets: masses via astrometry (SIM); optical photons (TPF-Coronagraph); and mid-IR photons (TPF-Interferometer/Darwin). JWST will play an important role in follow-up activities looking at ground based, COROT, and Kepler transits; making coronagraphic searches for hot, young Jupiters; and studying proto-planetary and debris disks.

The exact observing plan for SIM's planet searches will make use of data from precursor missions, COROT and Kepler in particular. For example, the number of Earths in the habitable zone will inform the strategy for searching numbers of stars to find those planets most like the Earth. SIM will find many 1-10 M_{Earth} planets outside the habitable zone where Kepler and RV surveys are unlikely to have much success.

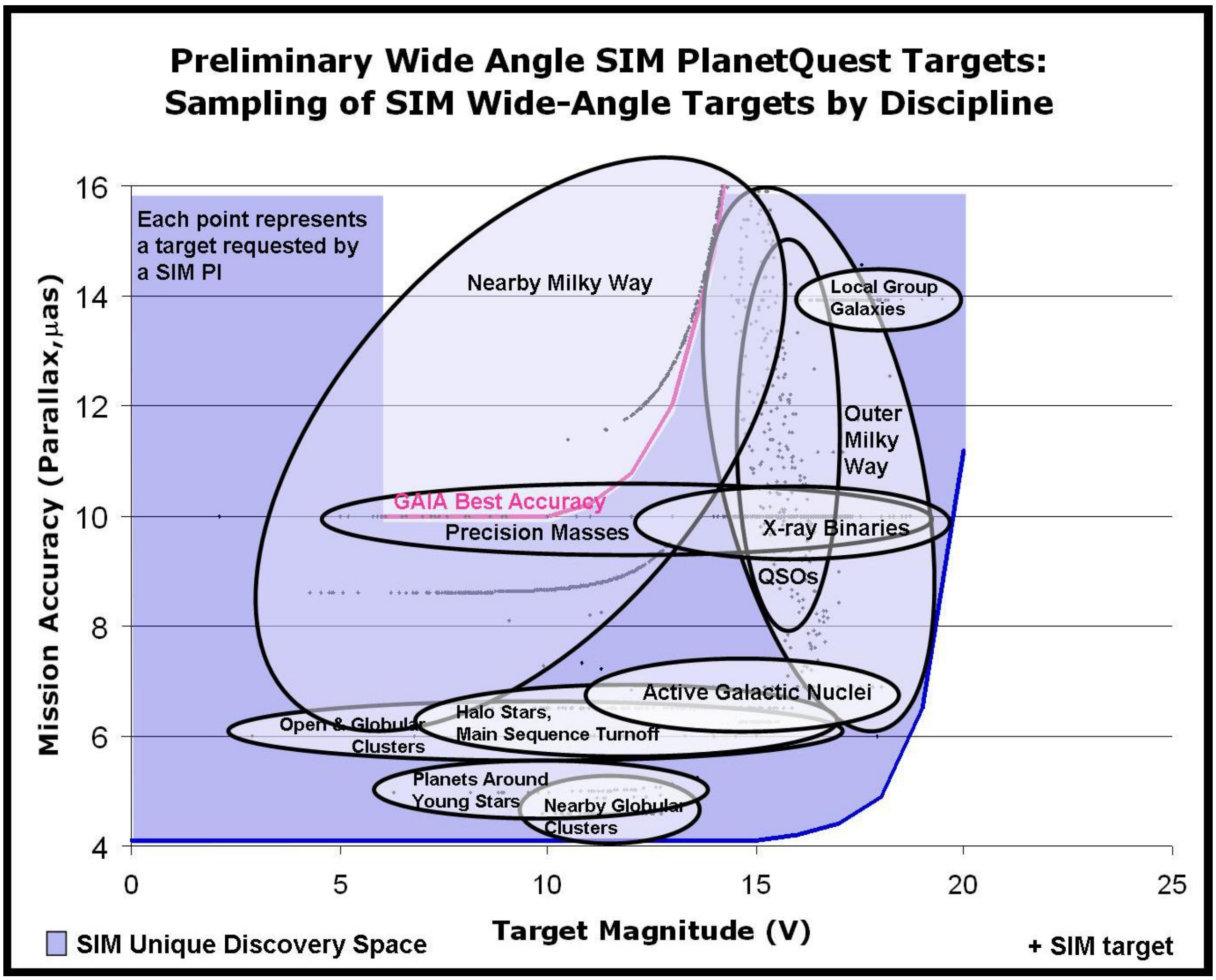

Fig. 4: SIM Science Team selected targets are shown on this plot of desired mission accuracy vs. target brightness. The targets are selected to exploit the new parameter space that SIM opens (blue curve). For comparison, GAIA will observe a very large number of targets (light area) to the left of the GAIA curve (pink). GAIA's bright star limit ranges from magnitude ~3-7.

GAIA is an ESA space astrometry mission, a follow on and major upgrade of the very successful Hipparcos mission. While GAIA and SIM both make very precise position measurements of stars, the capabilities of the two missions are quite different (Figure 4). GAIA's strength is in numbers. The mission will survey ~1 billion stars, with both astrometric and radial velocity measurements. GAIA is a global astrometric mission, with a goal of ~16 μas at 15 mag. The nominal mission for GAIA is launch in 2011 and end in 2020, a mission life of ~9 years. Visit http://www.rssd.esa.int/index.php?project=GAIA&page=Info_sheets_accuracy for more details.

At fainter magnitudes GAIA accuracy degrades significantly because of CCD read noise and dark current and the relatively short integration time spent per object. At 18 mag the accuracy falls to ~200 μas whereas SIM will still be capable of 6 μas accuracy. Brighter than 15 mag, GAIA's accuracy is ~10 μas. The accuracy of GAIA for bright stars is a rather complex function. GAIA is a survey instrument and observes all stars in the same way. Bright stars saturate the CCDs and useful astrometric information is degraded unless the target drifts through a small number of CCDs that have neutral density filters.

JWST, expected to launch in 2013, will offer coronagraph modes for its two infrared imaging instruments. Even though JWST's segmented primary mirror is poorly suited to high contrast coronagraphy, JWST's coronagraphs can access the bright 4.8 micron emission feature expected in the spectra of giant planets and brown dwarfs enabling the detection of substellar companions at contrast ratios of 10^{-5} to 10^{-6}. Detailed performance estimates show that JWST should be able to detect warm planets in nearby young stellar associations at radii greater than 0.7 arcsec, and perhaps even a few old (5 Gyr) Jupiter-mass planets around nearby, late-M type stars (Green et al., 2005). JWST will study early and late phases of planet system evolution revealed by emission from pre-planetary disks and debris disks. The presence of planets by their gravitational effect on debris disk structure in systems which are too dusty for study by SIM and TPF may be inferred from JWST observations. JWST may obtain intrinsic spectra of hot young gas giants in favorable cases It will be able to follow up on Kepler transits of giant planets to study the absorption spectrum of any planetary atmosphere.

SIM and TPF observations complement each other in several ways. Just as SIM's science program is enhanced by the use of Kepler data, SIM data will enhance the science from TPF. Most importantly, SIM will complement TPF scientifically by determining masses for many planets identified by TPF. Perhaps just as important, SIM will identify planetary systems for TPF to avoid. These include planetary systems where a Jovian planet would dynamically preclude the existence of a terrestrial planet in the habitable zone. TPF-C can detect planets down to and perhaps slightly less than one Earth radius, but for some nearby stars, those whose habitable zone is very large, SIM sensitivity is sufficient so that non-detection can preclude a planet detectable at the nominal contrast of 10^{-10}. Such a system might not be a good one for an intensive TPF-C program.

Astrophysics and Cosmology

The big questions in cosmology today involve the nature of Dark Matter and Dark Energy. Several of SIM's key projects investigate Dark Matter in the Milky Way and Local Group. Proper motion and parallax measurements are used to better determine the movement and distance of "test particle" stars in the Galaxy's halo, its companion dwarf ellipticals, and in other members of the Local Group.

Parallax measurements of standard candles, especially Cepheid variables and RR Lyrae stars, will reduce uncertainties in the Hubble Constant to 2%, better than other projected missions including Herschel/Planck. At this level theories of the equation of state of the universe can be tested. With such testing, the unexcluded theoretical explanations of Dark Energy will be significantly reduced.

It is crucial to our understanding of stellar astrophysics that stellar masses be determined to high accuracy. Knowing the masses of main sequence stars answers basic stellar astrophysics questions such as *What is the biggest star? How is the mass of a stellar nursery partitioned into various types of stars?* and, *What is the mass content of the Galaxy and how does it evolve?*

The principal goals of the MASSIF (Masses and Stellar Systems with Interferometry, (Todd J. Henry, P. I.) key project are to (1) define the mass-luminosity relation for main sequence stars in five fundamental clusters so that effects of age and metallicity can be mapped (Trapezium, TW Hydrae, Pleiades, Hyades, and M67), and (2) determine accurate masses for representative examples of nearly every type of star, stellar descendant, or brown dwarf in the Galaxy. To reach these goals SIM will measure masses with errors of 1% or less for roughly 200 stars, which will allow a challenge of stellar astrophysics models more severe than ever before. SIM will also investigate exotic targets such as supergiants and black holes to further understanding of these rare but intriguing objects.

An ensemble of mass-luminosity relations will allow accurate estimates for the masses of stars with extrasolar planets, and consequently, accurate estimates for the planet masses.

Using SIM, the Masses and Luminosities of X-Ray Binaries (Andreas Quirrenbach, P. I.) project will perform narrow-angle observations of several X-ray binaries to determine their orbits, and will observe 25-30 X-ray binary systems in wide-angle mode to measure their distances and proper motions. The project will:

- Determine the orbits of two black hole systems to measure the black hole masses.
- Obtain precise mass measurements for two neutron star systems to constrain neutron star equations of state.
- Determine the distances and thus luminosities of selected representatives of various classes of X-ray binaries (black holes, neutron stars, jet sources).
- Measure proper motions, allowing for an estimate of the age of the population.

Narrow-angle observations of black hole systems provide a direct test of the dynamical mass estimates on which the black hole evidence is based. When combined with X-ray data, mass measurements may provide additional constraints on the black hole spin. Precise mass determinations of neutron star systems can address the question of whether neutron stars can be significantly more massive than 1.4 solar masses.

The wide-angle observations will probe the Galactic distribution of X-ray binaries through parallaxes and proper motions. They will also eliminate the uncertainties in the luminosities of individual sources, which is currently up to a full order of magnitude. This will enable more detailed comparisons of X-ray observations to physical models.

SIM's project Exceptional Stars Origins, Companions, Masses and Planets (Shrinivas R. Kulkarni, P. I.) will study the formation, nature, and planetary companions of the exotic endpoints of stellar evolution. This project will determine the parallax and orbital inclination of several iron-deficient post-AGB stars, whose peculiar abundances and infrared excesses are evidence that they are accreting gas depleted of dust from a circumbinary disk. The circumbinary disks seem favorable sites for planet formation.

The primary goal of the Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Microlensing (Andrew P. Gould, P. I.) key project is to make a complete census of the stellar population of the Galaxy, including both ordinary stars and "dark" stars.

The only way to examine the field population of these stars is through microlensing, the deflection of light from a visible star in the background by an object (dark or not) in the foreground. When lensed, there are two images of the background star. Although these images cannot be resolved when the lens has a stellar mass, the lensing effect can be detected in two ways: photometrically, i.e. by measuring the magnification of the source by the lens, and astrometrically, i.e. by measuring the shift in the centroid of the two images. With SIM's astrometric measurements of the centroid, it is possible to break the microlensing degeneracy and allow detailed interpretation of individual microlensing events. This investigation will thus develop a detailed census of the dark and luminous stellar population of the Galaxy.

The SIM key project Anchoring the Population II Distance Scale: Accurate Ages for Globular Clusters (Brian C. Chaboyer, P. I.) will obtain accurate parallaxes to a number of Population II objects (globular clusters and field stars in the halo) resulting in a significant improvement in the Population II distance scale. Supporting theoretical work and groundbased observations will diminish the error in the measured ages of the Galaxy's oldest stars from 2 Gyr to 0.6 Gyr, and provide a critical test of certain cosmological theories. The early star formation history of the Galaxy will also be probed.

SIM's Open and Globular Cluster Distances for Extragalactic, Galactic, and Stellar Astrophysics (Guy S. Worthey, P. I.) project obtains parallax distances to a set of star clusters. One important goal is to pinpoint the zero point of the distance scale for main-sequence fitting. Another goal is to improve stellar evolutionary isochrones and integrated light models. The clusters themselves will be used to address unsolved problems of late-stage stellar evolution and Galactic and extragalactic chemical evolution. The clusters to be observed are chosen to span the widest possible range of abundance and age, to be as rich as possible, and to be as well-studied as possible.

This project will solve all distance-scale issues involving main-sequence fitting. It will also vastly improve the precision of distance measurement techniques that depend on stellar colors or luminosity functions such as the surface brightness fluctuation magnitude method for local galaxies. In combination with other (guest observer) SIM projects to pinpoint RR Lyrae and Cepheid distances, one-percent extragalactic distances will be within grasp, with a corresponding improvement in the precision of measurements of galaxy luminosities, sizes, large-scale flows, and dark matter content and a corresponding improvement in the cosmological parameters.

The SIM key project Taking Measure of the Milky Way (Steven R. Majewski, P. I.) will make definitive measurements of fundamental structural and dynamical parameters of our home galaxy, the Milky Way. The suite of experiments will utilize observations of distant giant stars in clusters and satellite galaxies, complemented by data for SIM Astrometric Grid stars, to characterize all of the major components (bulge, disk, halo, satellite system) of the Milky Way.

Specifically, the goals are:

1. To determine the mass distribution of the Galaxy, which is dominated by the presence of dark matter. SIM will measure
   a. tidal debris from dwarf satellites, notably the Sagittarius dwarf, mapping the shape, mass and extent of the Milky Way's dark halo out to 250 kpc;
   b. transverse motions for globular clusters not included in the Population II distance scale key project, mapping the Milky Way's inner halo;
   c. the relative contribution of the disk and halo to the overall gravitational potential;
   d. the local volume and surface mass-density of the disk, for model-independent comparisons with inventories of stars and gas in the solar neighborhood.
2. To measure fundamental dynamical properties of the Milky Way, notably
   a. the pattern speed of the central bar;
   b. the rotation field and velocity-dispersion tensor in the disk;
   c. the kinematics (mean rotational velocity and velocity dispersion tensor) of the halo as a function of position
3. To provide independent, high-accuracy determinations of two fundamental parameters that play a central role in virtually every problem in Galactic astronomy, namely
   a. the Solar Radius or the distance to the center of the Milky Way, R_0
   b. the Sun's angular velocity around the Galactic center, ω_0

SIM's key project Dynamical Observations of Galaxies (SIMDOG) (Edward J. Shaya, P. I.) will be used to obtain proper motions for a sample of 27 galaxies; the first optical proper motion measurements of galaxies beyond the satellite system of the Milky Way. SIM measurements lead to knowledge of the full six-dimensional position and velocity vector of each galaxy. In conjunction with new gravitational flow models, the result will be the first total mass measurements of individual galaxies. This SIM study will lead to vastly improved determinations of individual galaxy masses, halo sizes, and the spatial distribution of dark matter.

This project will derive distances at the level of seven percent for all the target galaxies using two methods: from the luminosity of the tip of the red giant branch of old metal-poor stars and from the Balmer line equivalent widths of A,B supergiants, the very stars used for the SIM proper motion studies. With this anticipated level of accuracy, we will locate galaxies to better than 300 kpc across the ~4 Mpc region of interest. This galaxy localization uncertainty is comparable to the anticipated dimensions of halos. One can expect to resolve the mass of groups into the masses of individual galaxies.

The SIM key project Binary Black Holes, Accretion Disks and Relativistic Jets: Photocenters of Nearby Active Galactic Nuclei (AGN) and Quasars (Ann E. Wehrle, P. I.) will address the following three key questions.
1. *Does the most compact optical emission from an AGN come from an accretion disk or from a relativistic jet?*
2. *Does the separation of the radio core and optical photocenter of the quasars used for the reference frame tie change on the timescales of their photometric variability, or is the separation stable at the level of a few microarcseconds?*
3. *Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers?*

Questions 1 and 2 will be answered with global and differential astrometry as follows. With global astrometry, radio (International Celestial Reference Frame) and optical (SIM) positions of radio-loud quasars can be compared at the sub-milliarcsecond level (radio ~70-100 μas; optical ~4-10 μas). Changes in radio structure originate in moving relativistically beamed features in a jet; it is to be expected that similar behavior will be observed in optical structure. SIM will also measure any color-dependent position shifts across the optical waveband. This will prove to be a powerful diagnostic tool for AGN structure on scales of a few microarcseconds. Interior motion and associated photocenter changes of the objects in the reference frames affects the quality of the frame tie, hence, it is critical that the underlying physics should be studied in detail using bright archetypal objects such as 3C273 and 3C345, as representatives for the radio-loud core-dominated quasar class.

Question 3 has central importance to understanding the onset and evolution of non-thermal activity in galactic nuclei. An entire AGN black hole system may be in orbit about another similar system, as might occur near the end of a galactic merger. How large is the astrometric signature? Rough estimates, based on the circumstantial evidence currently available, indicate that displacements of 10 μas or more (readily detectable with SIM) may be present in a number of AGN.

The Astrophysics of Reference Frame Tie Objects (Kenneth L. Johnston, P. I.) key project will investigate the underlying physics of SIM grid objects. This project assists the SIM team in general to establish an absolute coordinate system for all SIM observations. Extragalactic objects in the SIM grid will be used to tie the SIM reference frame to the quasi-inertial reference frame defined by extragalactic objects and to remove any residual frame rotation with respect to the extragalactic frame. The following questions concerning the physics of reference frame tie objects will be investigated.

1. *What is the origin of optical emission in quasars?*
2. *Are the optical photo-centers of quasars compact and positionally stable on the microarcsecond level?*
3. *Are binary black hole mergers responsible for quasars?*
4. *What is(are) the emission mechanism(s) responsible for generating radio emission in chromospherically active stars. Is the emission thermal, relativistic synchrotron, or gyro-synchrotron?*
5. *What causes the transition of spherically symmetric Asymptotic Giant Branch (AGB) stars to asymmetric planetary nebulae (PNe)?*

SIM will be the first space astrophysics instrument to provide a capability for synthesis imaging at optical wavelengths, offering the promise of imaging high-surface-brightness targets with more than four times the best resolution attainable with the Advanced Camera on the Hubble Space Telescope. Synthesis Imaging at Optical Wavelength with SIM (Ronald J. Allen, P. I.) will collect data from SIM's two baselines and combine observations taken at many small increments in roll angle to image a field of view of ~1" with a resolution of FWHM approximately 0.008" at a wavelength of 500 nm.

SIM imaging will be especially useful on crowded fields containing many high-brightness targets. Such fields include the central regions of galaxies out to the Virgo Cluster (including active nuclei and jets), and the swarms of stars in the cores of Galactic globular clusters. There are indications that the central regions of some globular clusters may contain black holes, similar to the situation currently thought to occur in the centers of many galaxies. These massive objects dramatically affect the motions of nearby stars. Images made with SIM at several epochs spread over the lifetime of the mission will yield positions, proper motions, and perhaps even accelerations of cluster stars, providing unique new information on the masses of central black holes.

The SIM project A New Approach to Microarcsecond Astrometry with SIM Allowing Early Mission Narrow Angle Measurements of Compelling Astronomical Targets (Stuart Shaklan, P. I.) demonstrates a technique for narrow angle astrometry that does not rely on the measurement of grid stars. This technique, called Gridless Narrow Angle Astrometry (GNAA) can obtain microarcsecond accuracy and can detect extra-solar planets and other exciting objects with a few days of observation.

Gridless narrow angle astrometry with SIM is simply the application of traditional single-telescope narrow angle techniques to SIM's narrow angle optical path delay measurements. The GNAA technique will be used to observe short-term periodic signals, including known and potential extra-solar planets, the black-hole Cyg X-1 (P = 5.6 d), as well as radio and X-ray binary systems, e.g. the Be star LSI 61303 (P = 26.5 d), and similarly V725 Tau, X Per, V801 Cen, HD 63666, HD 91188, all with periods < 35 d.

Overall Science Program

The SIM Science Team was selected via a NASA Announcement of Opportunity (AO), in November 2000. The Team comprises the Principal Investigators of ten Key Projects and five Mission Scientists contributing their expertise to specific areas of the mission. Their science programs cover a wide range of topics in galactic and extragalactic astronomy.

The pie chart in Figure 5 shows the allocation of SIM time for the baseline 5-year mission. Within the selected program of Key Projects, the distribution of observing time between the various Key Projects is summarized there. Planet finding programs together take up 39% of the presently allocated time and more general astrophysics programs take up 61% of the allocated time. The available time comfortably completes the revised key projects in both planet search and astrophysics. Since only about half of the available observing time has been allocated to Key Projects so far, the remaining time will be allocated to Legacy & General Observer (GO) investigations in the future. In addition, Archival Research investigations will be invited after SIM is in flight.

SIM is designed with an expendables-life of 10 years, to leave open the option of a longer mission. Under a ten-year mission scenario, there would be the possibility of entertaining many additional projects, greatly increased GO time, further improvements in the astrometric grid solution, and benefits including improvements to the orbit determinations, proper motions, and parallaxes of target objects.

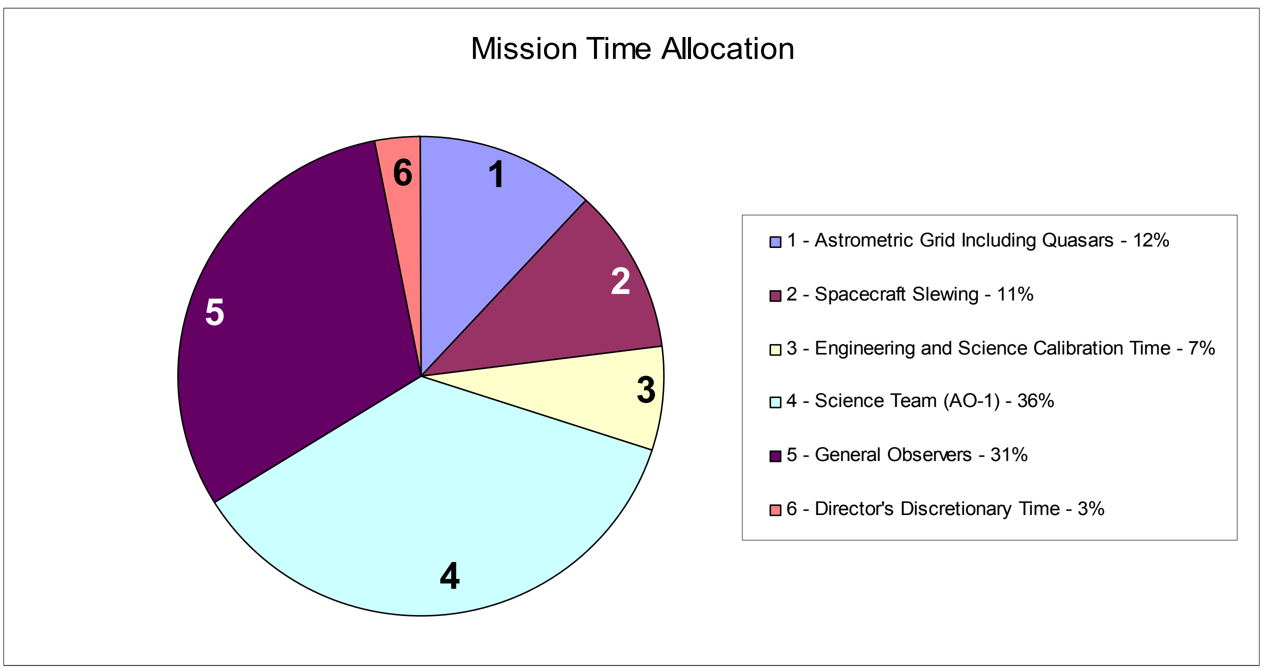

Fig. 5: The pie-chart shows the total distribution of observing time on SIM and includes both the existing program (AO-1) plus time for projects to be selected via future calls for proposals (General Observers).

While the power of SIM is well-illustrated by the approved programs, the potential with SIM is far from exhausted. Two examples, at extremes of distance, include the rotational parallaxes of nearby spiral galaxies and general relativistic effects due to the Sun and planets. Rotational parallax measurements involve the determination of the proper motions of sets of stars in intermediate to late-type spirals. These data, combined with ground based radial velocity data, permit the determination of distances to accuracy of a few percent and with complete independence from luminosity-based distance indicators (and thus providing a means for further calibrating the latter).

There are many areas of galactic astronomy where SIM offers potential break-through measurements. The capability of SIM to measure distances and hence absolute luminosities of sources anywhere in the Galaxy can be extended to study of countless rare and poorly understood types and evolutionary stages of stars, systems, and phenomena. The field of binary stars offers a rich range of opportunities for programs to better understand their dynamics and evolution.

4. TECHNOLOGY DEVELOPMENT

This adventure of discovery will be enabled by an explosive growth of innovative technology, as exciting in its own right as the underlying scientific quest. SIM-PlanetQuest (see Figure 1) drives the state-of-the-art in optomechanical and optoelectronic systems as well as presenting daunting challenges in precise stabilization of lightweight deployable structures and coordinated computer control of numerous optical surfaces. SIM's technology has been developed over the past ten years, and is now complete, with technology goals substantially surpassed, providing a comfortable margin for the planned observations as summarized in this paper and presented in detail in reference [10].

SIM's design and performance are summarized in the table:

Table 2: SIM Design and Performance

Science Interferometer Baseline	9 m
Guide Interferometer Baselines	7.2 m
Wavelength range	0.4 – 1.0 mm
Telescope Aperture	0.30 m diameter
Astrometric Field of Regard	15 degrees
Narrow Angle Field of Regard	1 degree
Detector	Si CCD
Orbit	Earth-trailing solar orbit
Science Mission Duration	5 years
Global Astrometric Grid & Wide Angle Astrometry	4 µas mission accuracy
Narrow Angle & Planet-finding Astrometry (1°)	1 µas single measurement accuracy
Limiting Magnitude	20 mag

More information on SIM is available at: http://sim.jpl.nasa.gov

Technology Completed

The SIM technology development program took the better part of a decade to complete. Eight technology Gates (Table 3 and Figure 6) were established by NASA Headquarters representing significant milestones in the project's technology development, completion of which would signify the project's readiness to enter full scale development (Phase C/D in NASA vernacular). Each of these technology gates had specific performance criteria, due dates, and completion evaluation criteria, and were carefully reviewed and evaluated by a NASA Headquarters appointed external independent review team. Completion of these Gates constitutes demonstration that a NASA Technology Readiness Level (TRL)[11] of six (out of nine levels) has been reached, signifying readiness to make the commitment for flight hardware development.

This program resulted in component, subsystem, and system-level demonstrations of full SIM instrument capability to achieve better than 1 µas single-measurement astrometric performance over small (~1°) fields of regard (current estimate is 0.7 µas) and better than 4 µas five-year mission accuracy over the full sky (current estimate is 2.3 µas), to visual magnitude 20 stars and with instrument systematic errors below 0.1 µas. Further details of the SIM technology development program are presented in Laskin[12],[13].

These eight Technology Gates demonstrate not only system performance in relevant environments but also demonstrate the methodology that will be used to test and demonstrate performance of the flight system.

Table 3: Accomplishment of Technology Gates Against Original Due Dates Stated in May 2001 Letter

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

Legend
pm = picometer
mK = milliKelvin
dB = decibel (50dB = factor of 300)

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

All eight of these Technology Gates have now been completed, with the last of the eight gates being completed in July 2005[11, 12]. All eight Gates either met or exceeded their performance criteria and were completed on schedule, a rather significant accomplishment for an advanced technology development program.

This success required that two grand technological challenges be met and overcome:

(1) picometer level sensing of stellar fringe position and optical element relative positions over meters of separation distance
(2) nanometer level control and stabilization of optical elements on a lightweight flexible structure

A third significant technical challenge has to do with overall instrument complexity and the implications for interferometer integration and test.

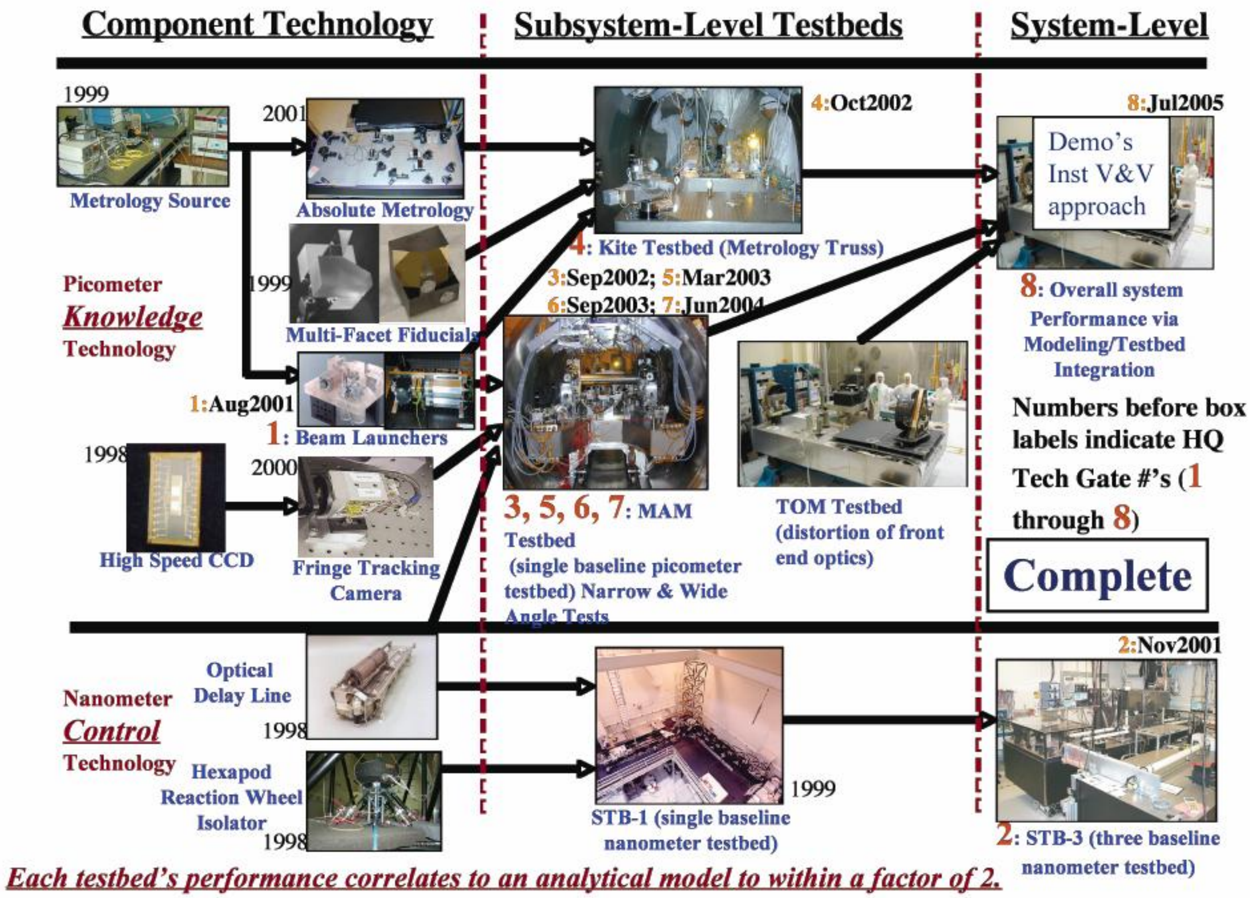

Fig. 6: As listed in Table 1, SIM's NASA-mandated technology gates have been passed, on schedule, at the component level, subsystem level, and system level. Technology development is complete.

SIM is presently reducing engineering risk by meeting the following milestones (Figure 7):
Formulation Phase (Pre-NAR [Non-Advocate Review]):

- EM1: External Metrology Beam Launcher Brassboard
  - Meet qualification-level environmental and allocated performance – Done/Met
- EM2: Internal Metrology Beam Launcher Brassboard
  - Meet qualification-level environmental and allocated performance – Done/Met
- EM3: Metrology Source Assembly Validation
  - Meet qualification-level environmental and allocated performance – Done/Met
- EM4: Spectral Calibration Development Unit (SCDU)
  - Demonstrate flight-traceable fringe error calibration methodology & validate the model of wavelength-dependent measurement errors. – In Test
- EM5: Instrument Communication Hardware-Software Architecture Demo
  - Validate SIM's multi-processor communications system using two brassboard Integrated Flight Computers & Ring Bus interconnect and FSW [Flight Software] 2.0 with specific software functions as listed. – Tests Complete, Analyzing Results

Implementation Phase (Pre-CDR [Critical Design Review])

- EM6: Engineering Models for Metrology Fiducials
  - EM DCC (Double Corner Cube) & TCC (Triple Corner Cube) meeting flight requirements
  - Contract in place but limited to bonding demonstration at present.

- EM7: Metrology Source Engineering Models
    - Optical Bench; Fiber Splitters; Fiber Switches; Fiber Distribution Assembly; Laser Pump Module - All to flight performance requirements per table.
- EM8: Instrument/Mission Performance Prediction
    - Update of Tech Gate 8, demonstrates end-to-end verification using latest hardware results.
- EM9: Integration of spacecraft FSW Build-1 with Phase-1 of the spacecraft engineering model (EM) testbed (SCEMTB)
    - Demonstrates specific software functions on EM Data Management System & Real Time Controller hardware.

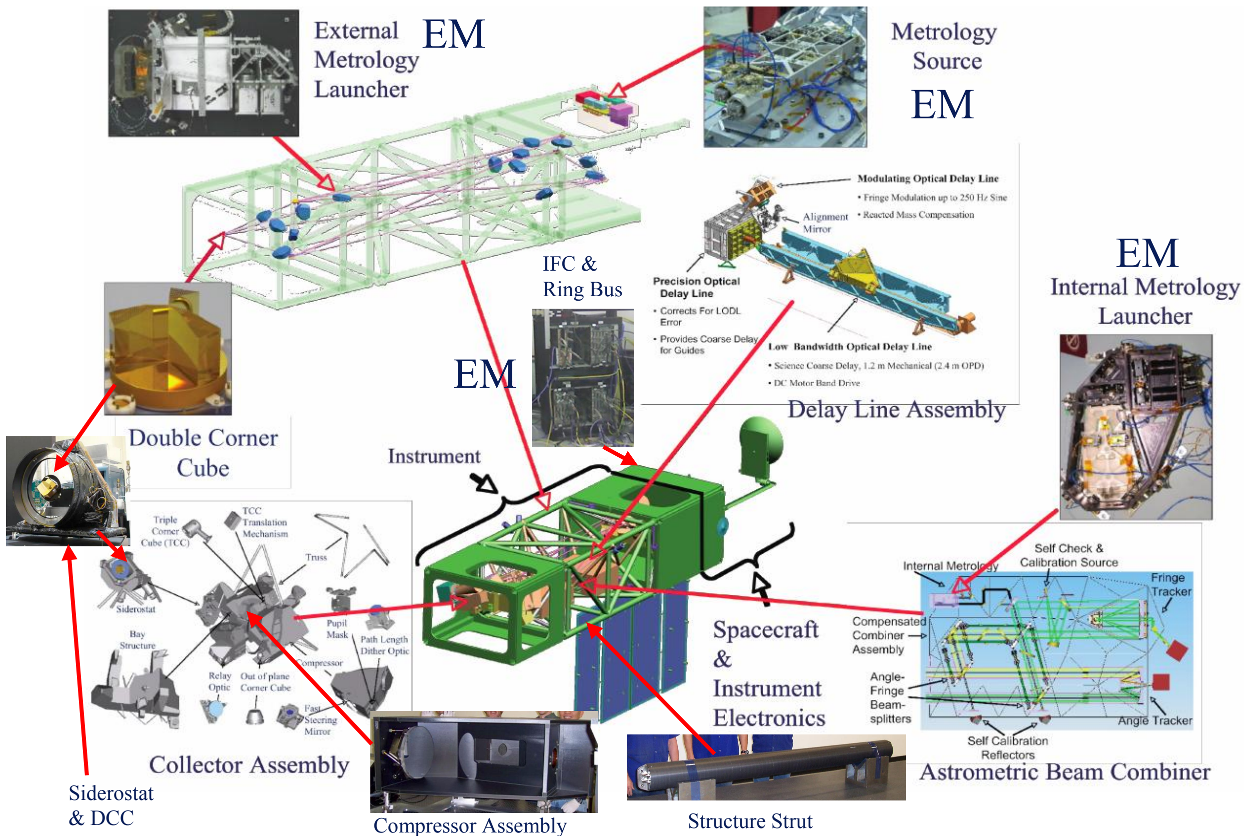

Fig. 7: Some NASA-mandated engineering milestones and their positions in sub-systems and systems are illustrated in this exploded view.

5. FLIGHT OPERATIONS PLANS

SIM will be boosted into an Earth-Trailing Solar Orbit during its launch phase. The design of the orbit is such that its distance from Earth will increase at the rate of 0.1 AU/year. Shortly after launch and deployment of the solar array and communications antenna, SIM will begin a two-month period of In-Orbit Checkout (IOC), during which many spacecraft and instrument systems will be turned on and characterized. Following IOC, the Science Verification phase of the mission commences. During this four-month period, the instrument and all of its subsystems will be calibrated (some several times). Sample measurements will be made and three full scans of the sky (outside the 60°-radius solar exclusion zone) will be made to begin the foundation of the astrometric grid, composed of 1302 K giant stars at distances of order 1 kpc.

Well in advance of launch, the Science Team and General Observers will have submitted their observation requests to the Reserved Observation Catalog. They will also prepare their desired schedules of observation of their target objects. Observations may be biased toward better parallax or proper motion results, if desired. SIM's Science Operations System will use their desired schedules to prepare a five-year and shorter schedules of measurements for the mission.

The process of uplinking a command sequence to SIM begins six weeks ahead of radiating the commands. By this time, observers have submitted minor revisions (e.g., target changes or substitutions, integrations times, spectral coverage, etc.) to the longer term plans. A final sequence of instrument and spacecraft commands is generated and then radiated to the spacecraft.

Provision has been made for both "regular" targets of opportunity (RTOOs) and "disruptive" (to the schedule encompassed by the sequence) targets of opportunity (DTOOs). Sequence updates can be generated and radiated in just a few days' time for TOOs. Microlensing events in Baade's Window are considered RTOOs, while microlensing events in the Magellanic Clouds, or a nova/supernova or other eruptive variable are considered DTOOs.

About three years after launch, planning will begin for continuing the goal mission's five additional years. Calls for General Observers will be made, including proposals for new key projects.

6. SUMMARY

Scientifically, SIM will open new vistas, including the discovery of Earth-mass planets in our galactic neighborhood. However, from the perspective of the mid-1990s, the technology necessary to make SIM a reality looked close to impossible to achieve. Unprecedented challenges in the fields of nanometer stabilization, picometer sensing, and complex system integration and test all presented themselves. Ten years later, all of these obstacles have been overcome, and SIM PlanetQuest technology is now in place. The feasibility of measuring star positions to microarcseconds has been firmly established, and the project looks forward to applying this wonderful technology to the flight system. Indeed, the technology transfer process is already well along.

The SIM mission is a key element in the Navigator Program[14]. SIM is the only currently planned mission that can unambiguously determine the masses of planets in *nearby* planetary systems, a key parameter in the identification of planets suitable for life as we know it. SIM also supports a broad astrophysics program that will enhance our knowledge of our Milky Way and other galaxies as well as significantly improving our calibration of the distance scales for measuring the universe. SIM's science is unique and distinct from any other NASA or ESA mission flying, in development, or in planning.

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