National Aeronautics and Space Administration

Planet Hunter

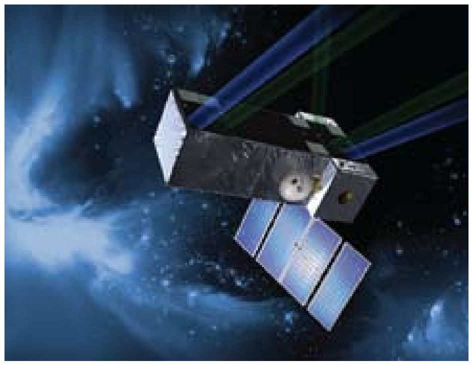
A Response to the Request for Information from Astro2010, the Astronomy and Astrophysics Decadal Survey Subcommittee on Programs

April 2009

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Response to the Request for Information from Astro2010,
Astronomy and Astrophysics Decadal Survey Subcommittee on Programs

Planet Hunter



Planet Hunter Project Team

James C. Marr, Project Manager,
Jet Propulsion Laboratory, California Institute of Technology
(818-393-1528; james.c.marr@jpl.nasa.gov)

Geoffrey Marcy, *Principal Investigator, University of California at Berkeley*
Michael Shao, *Instrument Scientist, Jet Propulsion Laboratory*
Cecilia Guiar, *Project System Engineer, Jet Propulsion Laboratory*
Renaud Goullioud, *Instrument Manager, Jet Propulsion Laboratory*
Frank Dekens, *Instrument System Engineer, Jet Propulsion Laboratory*

Planet Hunter Science Team

Charles A. Beichman, *California Institute of Technology*
Joseph H. Catanzarite, *Jet Propulsion Laboratory*
Deborah A. Fischer, *San Francisco State University*
Andrew W. Howard, *University of California at Berkeley*
Valery Makarov, *California Institute of Technology*
Geoffrey W. Marcy, *University of California at Berkeley*
Matthew W. Muterspaugh, *University of California at Berkeley*
Michael Shao, *Jet Propulsion Laboratory*
Stephen C. Unwin, *Jet Propulsion Laboratory*

Executive Summary

The Planet Hunter (PH) Astrophysics Strategic Mission Concept is a reduced-cost, reduced-capability (optimized for exoplanet science only) version of the SIM Lite Astrometric Observatory in which NASA has invested 15 years and $590M to bring technology, mission design and brassboard model hardware to a state where both it and PH are implementation-ready.

Planet Hunter is a pointed observatory that will, through astrometric measurements of nearby stars from a visual magnitude of –1.5 to 10, indirectly detect exoplanets, providing unambiguous masses and a full set of orbital parameters, accomplishing an exoplanet program identical to the exoplanet portion of the SIM Lite mission science program. The key science goals of PH are discussed in Section 1.

Based on the results of independently peer-reviewed technology achievements at the component, subsystem, and system level, PH will achieve narrow-angle astrometry single measurements at 1 µas RMS 1-sigma, with the ability to achieve < 0.2 µas 5-year mission accuracy (multiple measurements).

The recommended mission consists of a 6-m optical wavelength (450–950 nm) Michelson Stellar Interferometer (MSI) with 30-cm apertures, described in Section 2. It will launch on an intermediate-class EELV into an L2 orbit for a 5.4-year on-orbit lifetime.

No technology development remains, as discussed in Section 3. All technology was completed to TRL 6 in 2005, and signed off by NASA HQ following independent review. Brassboard (form, fit, function) models of most instrument elements have been built and tested to required performance or better.

PH, as a SIM Lite variant, is in NASA Phase B, prepared to complete a PDR and move into implementation in less than a year, and could launch as early as 2015. Extensive investment in technology and risk reduction allows cost estimates that are at a high level of fidelity. Project cost estimates conducted in the fall of 2008, presented in Section 6, involving multiple methods produced an average estimate of development cost-to-go of $900M plus launch services in FY09$. The operations cost range was $76M for 5.3 years of operations and 1 year of post-operations data archival. An independent estimate was conducted by the Aerospace Corporation under contract to the JPL Costing Office, producing multi-model based estimate of $1,140M plus launch services for development cost-to-go and $77M for operations (FY09$).

Planet Hunter, a SIM Lite variant, is an exoplanets-only mission that can provide the mass and orbits of Earths around nearby Sun-like stars; has low risk due to NASA investments in SIM; is cost-credible based on extensive design, development and testing; and is implementation-ready.

The Search for Habitable Worlds

- **Deep Search for planets down to one Earth mass in the habitable zone of 60 to 100 nearby Sun-like dwarf stars (meets the AAAC Exoplanet Task Force recommendation).**
- **Broad survey to characterize planetary systems around approximately 1,000 stars over the full range of spectral types and metallicities.**
- **Young planetary system characterization around 50 nearby young stars (<100Myr).**

Section 1. Key Science Goals

Planet Hunter Objectives and Rationale

Roughly 350 exoplanets have been found to date. None are Earth analogs. The Planet Hunter (PH) mission concept addresses the next major step — finding a large number of Earth analogs around nearby stars.

Planet Hunter is a reduced-capability, reduced-cost variant of the SIM Lite mission [1], optimized exclusively for exoplanet finding and characterization of planet mass and orbit. The PH design differs from SIM Lite's in that it has smaller science siderostats (30 cm vs. SIM Lite's 50 cm; since dim star performance is not required for Planet Hunter), has simpler electronics and software, and the observatory will be placed into an L2 halo orbit (vs. SIM Lite's Kepler-like solar drift away orbit). As a variant of SIM Lite, Planet Hunter uses the same technology developed over the past 12 years for the SIM mission and thus could be developed at low technical risk.

Planet Hunter performs microarcsecond (μas) astrometry during 5 years of on-orbit mission operations to accomplish a three-pronged exoplanet search:

– Deep search for planets down to one Earth mass in the habitable zone of 60 to 100 nearby Sun-like dwarf stars [7] (meets the objectives of the AAAC Exoplanet Task Force [2]);

– Broad survey to characterize planetary systems around approximately 1,000 stars over the full range of spectral types and metallicities [8]; and

– Young planetary systems around approximately 50 nearby young stars (<100Myr) [9].

Planet Hunter accomplishes these objectives during a 5-year mission using a 6-m Michelson stellar interferometer in an L2 halo orbit that is capable of 1.0 μas single-measurement accuracy and having a demonstrated instrument systematic noise floor of less than 0.035 μas one-sigma, yielding a Mission Detection Astrometric Signature (MDAS) of ~0.2 μas at a SNR of 5.8 for a < 1% False Alarm Probability (FAP). Of the 60 likely best target stars for PH, the most difficult star, with a one-Earth-mass planet at the luminosity-scaled equivalent of 1 AU, has an expected astrometric signature of 0.27 μas, which is above the 0.2 μas MDAS needed for a 1% FAP. At the inner edge of the habitable zone for this same star, the astrometric signature is 0.22 μas.

Astrometry is unique among methods for detection of exoplanets in that:

– Microarcsecond astrometry is the only mature technique capable of definitely detecting a reasonable number of Earth-like planets in the habitable zones of nearby Sun-like (F, G, K) stars and determining their masses and full set of orbital parameters.

– Astrometry becomes more sensitive as a planet's orbital semi-major axis increases due to the increasing amplitude of stellar motion about the common center-of-mass of the star-planet system, unlike radial velocity (RV), which becomes less sensitive with increasing planet–star distance. RV, at the current detection limit of ~1 m/s, can begin to penetrate the habitable zone of cooler M-dwarf stars, but will be challenged to penetrate the habitable zones of F, G & K dwarfs. Below 1 m/s, RV becomes dominated by stellar astrophysical noise that makes search for Earth analogs by RV, in most cases, impractical, if not impossible. On the other hand, long-duration RV data for PH targets will allow better handling of long period gas giants.

– Planets can't hide from microarcsecond astrometry as they can from other detection techniques such as transits and RV. Transits require the exoplanet's orbital plane to cross the line of sight (only ~0.5% of planetary systems will be so aligned). Direct detection methods require the planet to be outside the instrument's inner working angle and that exozodi interference be small.

– Microarcsecond astrometry provides the unambiguous mass and full orbital parameters for all planets above the instrument's detection threshold and with orbital periods less than 0.9 times the mission duration.

Recent double-blind exoplanet finding capability studies [3] have demonstrated the ability of astrometry to find Earth mass planets in the habitable zone of stars similar to the Sun, with complex planetary systems, at distances up to 10 pc. More recent results show comparable completeness and reliability (>90%) for stars on the current target list for Planet Hunter and SIM Lite (see Table 1-1). These results are based on four separate analysis teams selected competitively from around the country.

The recently completed Planet Hunter Astrophysics Strategic Mission Concept Study (PH ASMCS) examined a wide range of PH mission options, including different science instrument interferometer baselines, science siderostat sizes, and mission orbits. JPL Team X studies were completed on each of these concepts to evaluate their comparative feasibility and mission costs. The PH mission design presented in this document is the minimum mission capable of meeting the AAAC Exoplanet Task Force recommendations [2].

Planet Hunter responds directly to the recent (October 2007) recommendation of the AAAC Exoplanet Task Force [2] for an astrometric planet finding mission that would produce results within five to ten years.

Predicted Performance Verification

Planet Hunter will fly a 6-m Michelson stellar interferometer with 30-cm telescopes in an L2 halo orbit for a 5-year mission, with 80% of the mission time being available for science observations (remaining time used for engineering activities).

The current best estimate of the single-measurement astrometric precision of this instrument is 1.0 µas in an ~1100 second (18.3 minutes) measurement of a 7th magnitude or brighter target star relative to four 9th magnitude reference stars. The single-measurement accuracy of 1.0 µas in 1100 sec only specifies one parameter of PH's performance. An Earth–Sun system at 10 pc has an astrometric signature with a semimajor axis of 0.3 µas. To detect such a planet, we need a sufficient number of observations over a 5-year period so that the "mission" normal error is ~ 1/5 of 0.3 µas in order to obtain a five-sigma detection (< 1% FAP).

This mission normal error has several components: photon noise, instrument systematic noise, and astrophysical noise.

Table 1-1. *Planet Hunter target list.*

#	HIP ID	Spectral Type	Dist [pc]	Vmag	Earth µas@ EHZ
1	HIP 71683	G2 V	1.4	-0.3	2.74
2	HIP 71681	K1 V	1.4	1.3	1.98
3	HIP 8102	G8 V	3.7	3.5	0.62
4	HIP 88601A	K0- V	5.1	4.0	0.59
5	HIP 2021	G1 IV	7.5	2.8	0.57
6	HIP 99240	G6/8 IV	6.1	3.6	0.55
7	HIP 108870	K4/5 V	3.6	4.7	0.53
8	HIP 3821A	G0 V	6.0	3.4	0.49
9	HIP 81693A	G1 IV	10.8	2.8	0.48
10	HIP 86974	G5 IV	8.4	3.4	0.48
11	HIP 22449	F6 V	8.0	3.2	0.47
12	HIP 84405B	K(2) (III)	6.0	4.3	0.47
13	HIP 104217	K7 V	3.5	6.0	0.50
14	HIP 19849	K0/1 V	5.0	4.4	0.46
15	HIP 15510	G8 III	6.1	4.3	0.46
16	HIP 107556	A3mF2 IV:	11.8	2.8	0.45
17	HIP 96100	G9 V	5.8	4.7	0.40
18	HIP 27072	F6.5 V	9.0	3.6	0.39
19	HIP 14632	F9.5 V	10.5	4.1	0.38
20	HIP 14879A	F6 V	14.1	3.9	0.36
21	HIP 7751B	K0/4	8.2	5.1	0.37
22	HIP 73184	K4 V	5.9	5.7	0.38
23	HIP 44127	A7 V(n)	14.6	3.1	0.35
24	HIP 64924	G5 V	8.5	4.7	0.34
25	HIP 1599	G0 V	8.6	4.2	0.34
26	HIP 49908	K8 V	4.9	6.6	0.37
27	HIP 84709	K4 V	7.0	5.9	0.35
28	HIP 16852	F8 V	13.7	4.3	0.33
29	HIP 44248A	F5 IV-V	16.4	4.0	0.32
30	HIP 7981	K0 V	7.5	5.2	0.32
31	HIP 99461	K2 V	6.1	5.3	0.33
32	HIP 77257	G0 IV-V	11.8	4.4	0.32
33	HIP 64408	G3 V	20.5	4.9	0.32
34	HIP 93825A	F8/G0 V	17.9	4.2	0.31
35	HIP 28103	F2 V	15.0	3.7	0.31
36	HIP 71957	F2 V	18.7	3.9	0.31
37	HIP 105090	M1/2 V	4.0	6.7	0.34
38	HIP 15457	G5 V	9.2	4.8	0.31
39	HIP 42430A	G3/5 V	19.9	5.1	0.31
40	HIP 105858	F7 V	9.2	4.2	0.30
41	HIP 102485	F5 V	14.7	4.1	0.30
42	HIP 29271	G6 V	10.2	5.1	0.30
43	HIP 24813	G1 V	12.7	4.7	0.29
44	HIP 40702	F5 V	19.5	4.1	0.29
45	HIP 57443	G3/5 V	9.2	4.9	0.29
46	HIP 50954	F2/3 IV/V	16.2	4.0	0.28
47	HIP 84478	K5 V	6.0	6.3	0.30
48	HIP 17651	F3/5 V	17.9	4.2	0.28
49	HIP 77760	G0 V Fe-0.8...	15.9	4.6	0.28
50	HIP 16846A	K1 V	29.0	5.7	0.29
51	HIP 12114	K3 V	7.2	5.8	0.29
52	HIP 86796	G3 IV/V	15.3	5.2	0.28
53	HIP 84720A	G8/K0 V	8.8	5.5	0.28
54	HIP 59199	F1 V	14.8	4.0	0.27
55	HIP 47080	G8+ V	11.2	5.4	0.28
56	HIP 12843	F5/6 V	14.0	4.5	0.27
57	HIP 56997	G8 V	9.5	5.3	0.27
58	HIP 5336	K1 V Fe-2	7.6	5.2	0.27
59	HIP 67153	F3 V	19.3	4.2	0.26
60	HIP 99825	K3 V	8.8	5.7	0.27

Photon noise dominates but is known to average down as the square root of the number of observations.

Instrument systematics, which have been shown in SIM testbeds [4] to average down as the square root of the number of observing time to below 0.03 µas [Figure 1-1], even in the presence of significantly worse thermal instability than predicted for the in-flight mission.

Astrophysical noise comes primarily from two sources: star spots and planetary companions to some or all of the four or five reference stars.

Simulations of the effects of star spots [5] show that, the star spots do not introduce a significant astrometric error for stars up to five times more active than the Sun. A model of the Sun derived from 30-year records of sunspot numbers was used to generate astrometric and radial velocity "jitter." The resultant astrometric noise, averaged over 5 years, was 0.01 to 0.02 µas, well below the Planet Hunter MDAS of 0.2 µas or the 0.3 µas signature of an Earth around the Sun at 10 pc.

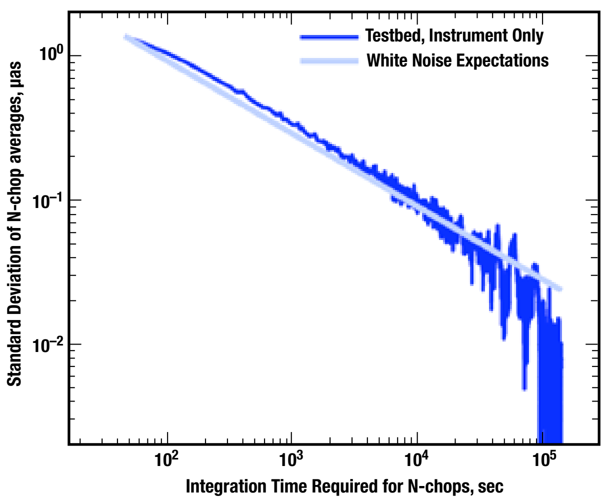


Figure 1-1. *MAM testbed data demonstrating instrument systematic error averages down with increasing observation time.*

Astrophysical noise from planets around reference stars falls into three categories: (1) The planets are too small to matter; (2) The planets have a large enough astrometric signature that it is detected, modeled, and removed, with no residual effect; and (3) One in 20 reference stars will have a planet that induces a reference star motion between 0.4 µas and 0.05 µas that cannot be detected at the 1% FAP, corrupting the average reference frame by <0.1 µas, which below is the 0.2 µas MDAS threshold.

Various observing strategies are available for Planet Hunter. The current baseline is to visit each target star 200 times (100 times on each of two orthogonal orientations of the Planet Hunter baseline), varying the observing time on each visit to a star to achieve the required astrometric sensitivity. Even for the brightest stars, a minimum of 200 visits are planned to allow resolving planet orbital parameters for up to ~5 planets. Several other observing strategies are possible, allowing tailoring of the observing strategy to the known characteristics of any particular star.

A candidate list of the best nearby stars for Planet Hunter is maintained but continues to evolve slowly as more information about each of the candidate stars is obtained (Table 1-1). The search strategy for the eventual final list is to sort the known nearby stars by the size of their astrometric signature resulting from a one-Earth-mass planet in a mid-habitable zone, allocating as much time (observation time per each of 200 visits) as needed for each star to detect the target minimum mass planet (e.g., one Earth mass), then proceeding down the star list until we either ran out of observing time or the mission accuracy exceeds the expected 0.2 µas MDAS.

Figure 1-2 shows the number of target stars that can be searched to a particular mass depth as a function of the percent of mission time allocated to that search depth. With 80% of the mission allocated to search to one Earth mass, the figure shows that ~80 stars can be searched. Other schemes might be to allocate only a portion of the mission time to search to one Earth mass with the remainder to used to search many more stars to shallower mass depth.

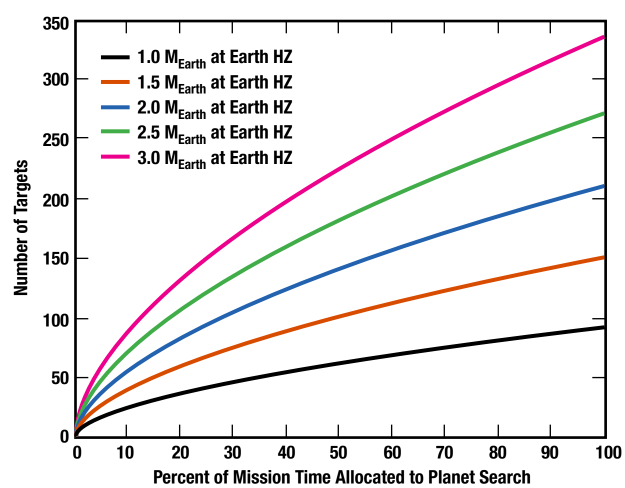


Figure 1-2. *Number of planets searched vs. time and mass search depth.*

This will need to be a decision based on the best exoplanet knowledge available at the time of launch.

Of the about 350 known exoplanets, few have masses less than 10 Earth masses and none are located within the habitable zone. We don't know η_{Earth}, the fraction of stars that have a terrestrial planet in the habitable zone. The first mission to have the capability to collect data on Earth-mass planets in the habitable zone will be Kepler, which is expected to find ~ 50 Earths if every one of the 100,000 stars it monitors has two planets in the habitable zone like our own solar system (Earth and Venus) and astrophysical noise allows their detection. With an average distance of 1 kpc, few, if any, of Kepler's Earths will be near enough to follow up with direct detection missions such as coronagraphs.

Should Kepler find that Earth-like planets are rare (η_{Earth} <0.1, for example), the Planet Hunter strategy described above might be modified to search a significantly larger number of stars down to only 1.5, 2.0 or perhaps even 3.0 Earth-mass planets in the habitable zone. The amount of observing time needed to search a star to one Earth mass is nine times as long as it takes to search for a three-Earth mass planet in the same orbit. In a search for planets having three Earth masses, Planet Hunter could search the nearest ~300 stars in 5 years [Figure 1-2].

While terrestrial exoplanets in the HZ haven't been detected yet, it is possible to make a rough educated guess about their frequency of occurrence based on the ~350 exoplanets we have found. These exoplanets obey a rough power law distribution in both mass and semimajor axis. The implication is that there are as many planets between 1 AU and 2 AU as there are between 0.5 AU and 1.0 AU. There are roughly as many planets in the mass range 0.1 to 0.2 Jupiter mass as there are between 0.2 to 0.4 Jupiter mass. The paper by Cumming et al. [6] describes our current best understanding of the mass and semimajor axis distribution of exoplanets.

The point is that the volume of phase space occupied by terrestrial planets in the HZ is a rather small volume of the total phase space for all planets. Theorists [Cumming 2007, Ida and Lin 2004a, 2004b, 2005] have also been modeling planet formation from a protoplanetary disk. As they vary the initial parameters of the disk, they observe a common theme: that terrestrial planets form with much greater frequency than Jupiters. Models of planet formation that produce a distribution of Jupiters and Saturns consistent with the known exoplanets result in ~ 5 times as many terrestrial planets (per unit volume of phase space) as Jupiters. Using this as a starting point, we calculate that ~80% of stars have at least one terrestrial planet, but only ~10% of stars have a terrestrial planet in the habitable zone. Planet Hunter's deep search will find dozens of terrestrial planets, of which a handful will be in the habitable zone (Figure 1-3).

PH Science Projects

Planet Hunter has three exoplanet science projects, analogous to the SIM Lite exoplanet program. The first program is the deep search for Earth clones as described above [1][7].

The second is a broad survey [1][8] of ~1000 stars to ~4 µas precision that would look for planets around a wide variety of stars, not just Sun-like dwarf stars. While unable to find one-Earth-mass planets in the habitable zone, it would have the sensitivity to detect 10 Earth-mass planets in long 5-year orbits. Radial velocity observations are challenged to find planets around early-type stars because the intrinsic RV noise from the star is 10~100s of m/s. Transit techniques are unlikely to find planets with large semi-major axes. The broad survey puts planet formation in the broader context of where planets are found other than around solar-like stars. This survey will be a factor of 10 more sensitive that Gaia's all-sky survey, which will be limited predominantly to the detection of Jovian planets around stars within ~100 pc.

The third exoplanet science program is the search for planets around ~50 young, < 100 Myr, stars, primarily T-Tauri stars [1][9]. When the first hot Jupiters were found, the presence of Jovian planets 0.05 AU from the parent star was totally unexpected. How did they get there? This program is designed to look for the existence and orbits of planets before the disk is totally dissipated, when

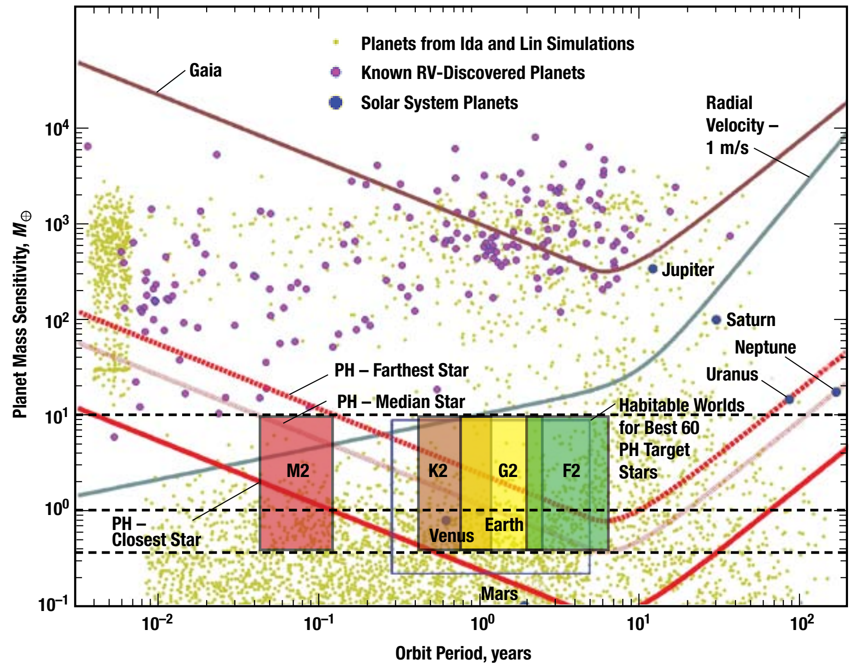


Figure 1–3. *Planet search space. Planets detectable above curves shown. Red curves show range of Planet Hunter stars (nearest, medium, farthest). Planet Hunter can find planets in the habitable zones of Sun-like stars not reachable by RV.*

planet disk and planet–planet interactions were still significant. Radial velocities cannot be used to find these planets because rapid stellar rotation and extremely active photospheres limit radial velocity accuracy to hundreds of meters per second. Similarly, photometric brightness fluctuations preclude transit detections. Fortunately, the astrometric signatures of gas giant planets ranging in mass from Saturn to Jupiter orbiting at 1–5 AU have values in the ranges of 10–100s of microarcsecond for the closest, young stars (10–100 Myr at 25–50 pc) and 5–35 microarcsecond for more distant, but even younger stars (1–10 Myr at 140 pc). Astrometric jitter due to star spots has been shown not to be a problem for the detection of gas giants. Individual targets will be screened for nebulosity, interfering companions, etc.

Summary

Scientifically, the path is clear. Astrometry is the next logical step in the step in the search for Earth analogs [2][10]. And as shown elsewhere in this paper, both Planet Hunter and SIM Lite can accomplish this objective, are ready technically, and can rapidly proceed to PDR and full development of the flight instrument.

References

[1] *SIM Lite Astrometric Observatory, From Earth-Like Planets to Dark Matter*, 2009, JPL 400-1360.
[2] Lunine, J., 2007, "Worlds Beyond: A Strategy for the Detection and Characterization of Exoplanets," AAAC Exoplanet Task Force.
[3] Traub, W. A. et al., "Detectability of Terrestrial Planets in Multi-Planet Systems Preliminary Report," PASP, 2009, submitted.
[4] Shao, M. and Nemati, B., "Sub-microarcsecond astrometry with SIM Lite, A testbed-based performance assessment," 2009 PASP. 121:41-44
[5] Catanzarite, J. et al., "Astrometric Detection of exo-Earths in the presence of stellar noise," SPIE, vol. 7013, July 2008.
[6] Cumming, et al., "The Keck Planet Search: Detectability and the Minimum Mass and Orbital Period Distribution of Extrasolar Planets," PASP 120: 531-554.

Astro2010 Science Frontiers Panels — White Papers
[7] Shao, M. Astrometric Detection of Earthlike Planets, #202.
[8] Kulkarni, S.R., No Planet Left Behind: Investigating Planetary Architecture and Diversity with SIM Lite, #178.
[9] Beichman, C.A., Formation and Evolution of Planetary Systems, #95.
[10] Shao, M., Direct Detection and Spectroscopy of Exo-Earths; The Need for High Angular Resolution and Other Observational Requirements, #249.

Section 2. Technical Overview

Planet Hunter is a simplified version of the SIM Lite Astrometric Observatory [1] that is optimized for nearby exoplanet detection. The Planet Hunter (PH) flight system (Figure 2-1), consisting of a spacecraft and a single large optical instrument, will be launched into orbit from the Eastern Test Range at the Cape Canaveral Air Force Station by an intermediate-class expendable launch vehicle. Planet Hunter will be placed into a halo orbit at the second Sun–Earth Lagrange point (L2), at about 1.5 million km from the Earth. The 2,660 kg current best estimate of the Planet Hunter mass, combined with 340 kg of propellant, results in a launch vehicle mass margin of 35%. In the L2 halo orbit, the flight system will receive continuous solar illumination, maintaining a stable thermal state and avoiding the occultations that would occur in an Earth orbit, therefore maximizing the science return. Planet Hunter will execute two trajectory corrections and one Lissajous orbit insertion maneuver to reach the Halo L2 orbit. Small periodic maneuvers (every 60 days) will be required for orbit maintenance.

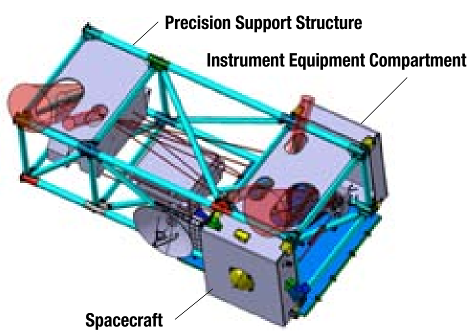


Figure 2–1. *The Planet Hunter flight system consists of a spacecraft and a single large optical instrument. The instrument components are mounted on the Precision Support Structure (PSS), which functions as a highly stable optical bench.*

The Planet Hunter instrument makes sequential angular measurements of the positions of stars projected along the interferometer baseline. All astrometric signals are two-dimensional on the sky, so every science measurement requires, at some later time, a repeated measurement with the baseline oriented approximately orthogonal to that of the first measurement. Individual stars are observed .

Narrow-angle differential astrometry is used for the search for exoplanets. A target star's motion is measured across many visits against a set of reference stars located in a two degree diameter field. Planet Hunter's extreme astrometric accuracy is enabled by two design factors: (1) rapid switching between target and reference effectively eliminates errors caused by long-term (e.g., thermal) drifts since the relevant time scale for the instrument thermal stability is reduced to ~90 seconds; and (2) differential measurement over small angles, and shared over several targets, eliminates a number of field-dependent errors that would be present over a large field. The reference stars are chosen to be astrometrically well described by position, proper motion, and parallax. The basic measurement is the delay difference between the target and a reference star, and the analysis uses these measurements pair-wise. See Figure 2-2.

The Principal Investigators will select the members of their science teams, plan the observations and screen the Reference stars prior to launch. The NASA Exoplanet Science Institute (NExScI) will prepare the 5-year schedule of observations, fitting observations requests, spacecraft maintenance, data downlinks, calibrations, and other flight activities into the schedule. NExScI will also perform the science data reduction and archiving.

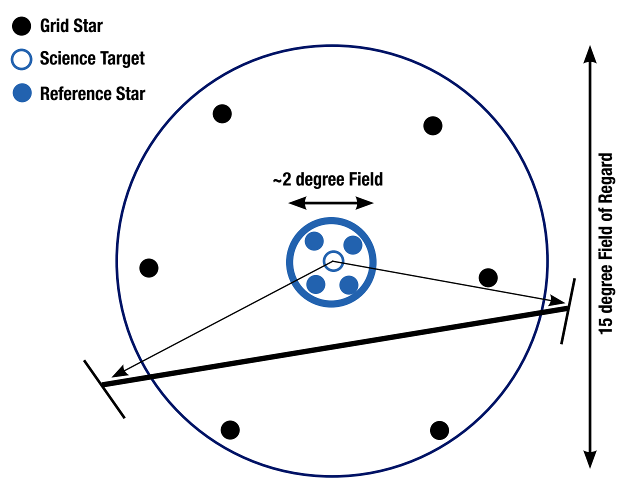


Figure 2-2. *Planet search observing scenario.*

Planet Hunter Instrument Overview

The Planet Hunter single optical instrument consists of four fundamental optical sensors: the Science Michelson stellar interferometer, the Guide-1 Michelson stellar interferometer, the Guide-2 high-accuracy star-tracking telescope and the external metrology, all mounted on a precision support structure (PSS), which functions as a highly stable optical bench. The science interferometer makes sequential astrometric measurements of the positions of stars that can be processed to represent angles on the sky projected along the interferometer baseline. Both during and between measurements, the science interferometer baseline orientation in inertial space is monitored by continuous observations of known, bright stars (referred to as "guide" stars) with the Guide-1 interferometer and Guide-2 telescope. The Guide-1 interferometer measures the instrument attitude to better than one micro-arcsecond in the science interferometer measuring direction by tracking a guide star in the same direction as the science target. The Guide-2 telescope measures the attitude to 50 µas in the other two directions by tracking a second guide star, roughly 90 degrees away from the first one. The science interferometer can be regarded as inertially fixed, to a precision better than the individual measurements, during and between science measurements. The Guide-1 interferometer baseline and the Guide-2 telescope line of sight are optically tied to the science interferometer by the external metrology truss system.

The science interferometer collects light from two 30-cm siderostats separated by the 6-m baseline. The siderostats articulate over an angular range of +3.75 degrees, giving the science interferometer a 15-degree-diameter field of regard (FOR). Once they are pointed at a star, these actuators are locked in place for the duration of the observation. In the optical train beyond the siderostat, each beam is compressed to a diameter of 4 cm using a confocal beam compressor. Next in the path is the fine steering mirror (FSM), which, compared to the siderostat, has a smaller range of motion but a much higher pointing resolution. It is used to track the star as the instrument attitude changes. The pathlength optic mechanism (POM) then folds the beam into the delay lines. The POM scans and stabilizes the starlight fringe by applying fine and relatively small delay modulations. Both the FSM and the POM are momentum-compensated so as not to disturb the interferometer while observing. The delay line provides the coarse correction to the optical path difference between the two arms, with a 40 cm mechanical range. With two such delay lines in one of the two collectors, a total optical path difference of 160 cm can be produced between the two sides, enabling interferometry within the 15 degrees FOR. The delay lines only move during retargeting to a new science object and are then locked into place. The other collector has static delay lines to keep the optical design symmetry in the two arms of the interferometer. Finally the beam is folded towards the center of the instrument where the two sides are combined to form fringes inside the astrometric beam combiner (ABC). The ABC contains the compensated combiner optics that recombines the light coming from the two collectors and forms interference fringes, the angle tracker camera that monitors tip-tilt for pointing control of the FSM, the internal metrology sensor that tracks the internal propagation pathlength from the siderostat to the combiner optics and the fringe tracker camera that integrates the interference fringes. See Figure 2-3.

The design for the Guide-1 interferometer is similar to the science interferometer, with a few simplifications. Because the spacecraft points the entire instrument to the Guide-1 star each time, there is no need for Guide-1 siderostats and delay lines. Hence, the first Guide-1 optic is the primary mirror of the confocal compressor. Due to packaging constraints, the Guide-1 baseline is reduced to 4.2 m. Finally, in Guide-1, the optical delay line is corrected using a single mirror on a coarse motor stage, since only 1 mm of travel is needed.

The Guide-2 telescope monitors the roll of the spacecraft about the vector pointing to the Guide-1 star. This roll is primarily caused by the drift of the attitude control system (ACS). Guide-2 has a siderostat similar to the science siderostat, with a

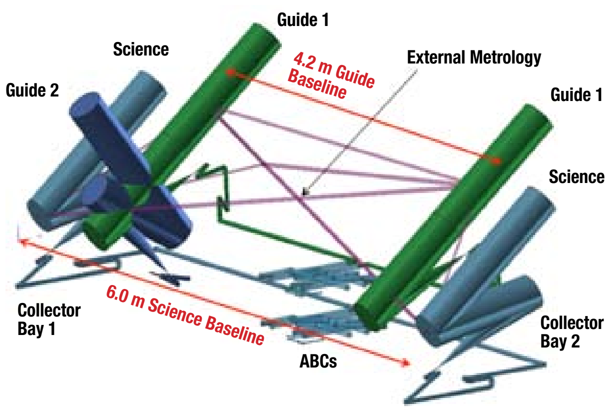


FIGURE 2-3. *The Planet Hunter optical instrument consists of four optical sensors: (1) the science Michelson stellar interferometer, (2) the Guide-1 Michelson stellar interferometer, (3) the Guide-2 high-accuracy star-tracking telescope, (4) and the external metrology system. These are mounted on the precision support structure (PSS), a highly stable optical bench (not shown).*

smaller 2 degree range but with two stages of actuation to provide the higher pointing resolution required to track the star while the ACS is drifting. The siderostat coarse state acquires the guide star and then locks, just as in the science siderostat. Then the fine stage takes over the role of the FSM in the interferometers. The approach results in fewer reflections and fits more readily on the already crowded bench.

The external metrology is needed to monitor the relative positions of Planet Hunter's fiducials, four of which define the science and guide interferometer baselines. The measurements are made using heterodyne metrology beam launchers using the same principles employed in internal metrology. However, rather than measure the path difference between the left and right arms of the interferometers, the external metrology beam launchers monitor the direct distance between each pair of fiducials. Nine beam launchers are used to monitor the external metrology truss, which has five fiducials.

The PSS is a highly stable structure accommodating the instrument components. It is the primary load-carrying member of the Planet Hunter flight system, and interfaces directly to the launch vehicle adapter. Beyond supporting the instrument subsystems, it maintains the thermal environment and provides solar shield and contamination protection. The PSS is a tubular truss-structure built up from carbon fiber reinforced plastic longerons and custom-designed titanium joint fittings.

The instrument real-time control system uses a Rad750-based computer located in the instrument equipment compartment, attached to the side of the PSS. Feedback control loops between the sensors located in the ABC and the actuators located in the collector bays, are implemented in C++ and are run at a few hundred hertz. The control electronics are distributed along the PSS to limit cabling length. The equipment compartment also hosts the laser metrology source for the internal and external metrology systems.

Other Instrument Variants Studied

Two other instrument configurations were studied during the concept study. These were: (1) a 5-m science baseline with 20-cm siderostats to fit in a smaller launch vehicle but otherwise the same as described above, and (2) the same as (1) but without the Guide-2 telescope.

Variant (1) operates the exactly the same as for the 6-m, 30-cm version but has lower throughput due to (a) less light gathering area due to smaller siderostats and lower single measurement accuracy due to the shorter baseline, both effects leading to the need for a greater number of observations to achieve the same planet detection level as the PH configuration described above. This lower throughput leads reduces the number of stars that can be detected to below the minimum target identified by the AAAC Exoplanet Task force (Lunine 2008) but does save a little money.

Variant (2) saves even more money but, without the Guide-2 telescope, throughput suffers even more due to the requirement to slew the entire spacecraft to different orientations to measure the target-reference star angles.

These variants are only slightly less expensive, yet suffer significant degradation in performance, both falling below the AAAC Exoplanet Task Force recommendation.

The PH version presented above, does meet the AAAC Exoplanet Task Force recommendation (as does the SIM Lite Astrometric Observatory), and represents the minimum cost configuration that will do so.

Planet Hunter Spacecraft

The Planet Hunter spacecraft is a three-axis stabilized, zero-momentum platform. It provides the standard spacecraft functions of attitude control, electrical power, thermal control, data management, telecommunications, and software. The graphite honeycomb spacecraft structure is shaped like an open bookshelf. The spacecraft open side faces the PSS and is thermally isolated from it with multilayer insulation. It houses four propellant tanks and four 90-N thrusters for orbit maintenance and insertion. The ACS provides space vehicle maneuvering to position the instrument to 3 arcsec one sigma and stability of 0.2 arcsec/100 sec to support the science mission, using four 150 Nms reaction wheels, a fully redundant scalable inertial reference unit (SIRU), and two catalog star trackers. Momentum unloading is achieved via four dual-thruster monopropellant modules, oriented and operated such that no delta-V is imparted during momentum wheel desaturation. Two-stage vibration isolation on the reaction wheels reduces jitter to the levels required by the interferometer.

The redundant command and data handling subsystem uses a Rad750 processor board to host the flight software and control the spacecraft. A 125 Gbit onboard data storage system provides more than twice the required 50 Gbit/week memory for science data.

Communication is by S-band low-gain omnidirectional antennas for both uplink and downlink for command and telemetry. Science data are downlinked using a small X-band mid-gain non-articulated antenna. Doppler ranging will be performed via the S-band uplink/downlink or S-band uplink/X-band downlink. Differential one-way (DOR) ranging is also supported via X-band or S-band.

Spacecraft power is provided via a dual-gimbaled, 16-square-meter solar array and lithium-ion batteries. The main function of the batteries is to provide power during launch and from launch vehicle separation to solar array deployment with some limited capability during safe modes. During normal operations, the 4400 W (end of life) solar array provides all onboard power. The end-of-life capability of the power system includes a 30% contingency on the current best estimate of the instrument power.

Planet Hunter Operation

Following orbit insertion, the spacecraft systems will be checked and tracking data collected to precisely determine the actual orbit achieved. Verification and calibration of the spacecraft and instrument will be performed during this in-orbit checkout (IOC)/science verification period, lasting about 5 months. Following this period, the Planet Hunter instrument will operate for 5 years, performing nearly continuous science observations over the entire celestial sphere.

Pointing of the flight system will be performed using reaction wheels, with small reaction control system thrusters used for desaturation. Pointing will be performed such that the viewing axis will never be within 45 degrees of the Sun to protect the viewing optics from heating. The flight system's velocity is required to be determined to an accuracy of 20 cm/sec or better for stellar aberration correction and the position to better than 50 km for parallax correction. This will be achieved using ranging and Doppler data obtained during two 8-hour tracking passes per week, using DSN 34-m ground stations. Science and engineering data will be recorded onboard and downloaded during the same tracking sessions. Frequency and duration of the S-band science data downlink sessions will be no more than four hours per week.

Summary

Planet Hunter, as a simplified version of SIM Lite and using the same completed technology, is technically mature and ready to proceed.

References

[1] Davidson, J.M. (editor), *SIM Lite Astrometric Observatory: From Earth-Like Planets to Dark Matter*, NASA, January 2009, Theme VI, Sections 16 through 20.
[2] Astrometric performance, operations, and planning reference papers on the SIM Lite website at URL: http://planetquest.jpl.nasa.gov/SIM/keyPubPapers/simBibliography/index.cfm?Cat=8

Section 3. Technology Drivers

The Planet Hunter (PH) architecture, as a simplified version of the SIM Lite Astrometric Observatory architecture, is enabled by the exceptional performance of the full SIM mission system (40% better than NRC Decadal "Goal" levels) that resulted from the stunningly successful SIM technology development program. The PH architecture uses only technology already developed and demonstrated for SIM at the time of its technology program completion in July 2005 and uses hardware designs demonstrated during SIM's engineering risk reduction program where a series of brassboards (form, fit, function to flight) were (or are being) built and subjected to environmental, performance, and life tests. There are no additional technology elements remaining to be developed for Planet Hunter. The Aerospace Corporation, in conjunction with the NASA Headquarters chartered SIM Lite independent cost estimate (October 2008 through January 2009), also performed an independent technical assessment. Their assessment was that "Most technologies [are] at TRL 6 or [are] anticipated to be by the end of FY09. Progress is appropriate for this stage of the project." (See Figure 3-1.) The following material briefly reviews the SIM technology development history. For a more detailed discussion, see References [1], [2] and [3].

SIM Technology Development Program

The SIM technology program begun in 1994 was geared toward demonstrating 1 μas astrometric precision, with a systematic error floor below 0.2 μas needed to support planned narrow-angle science. The program verified component, subsystem and system level technologies in both real-time nanometer fringe control and in picometer optical element position and fringe measurement. The

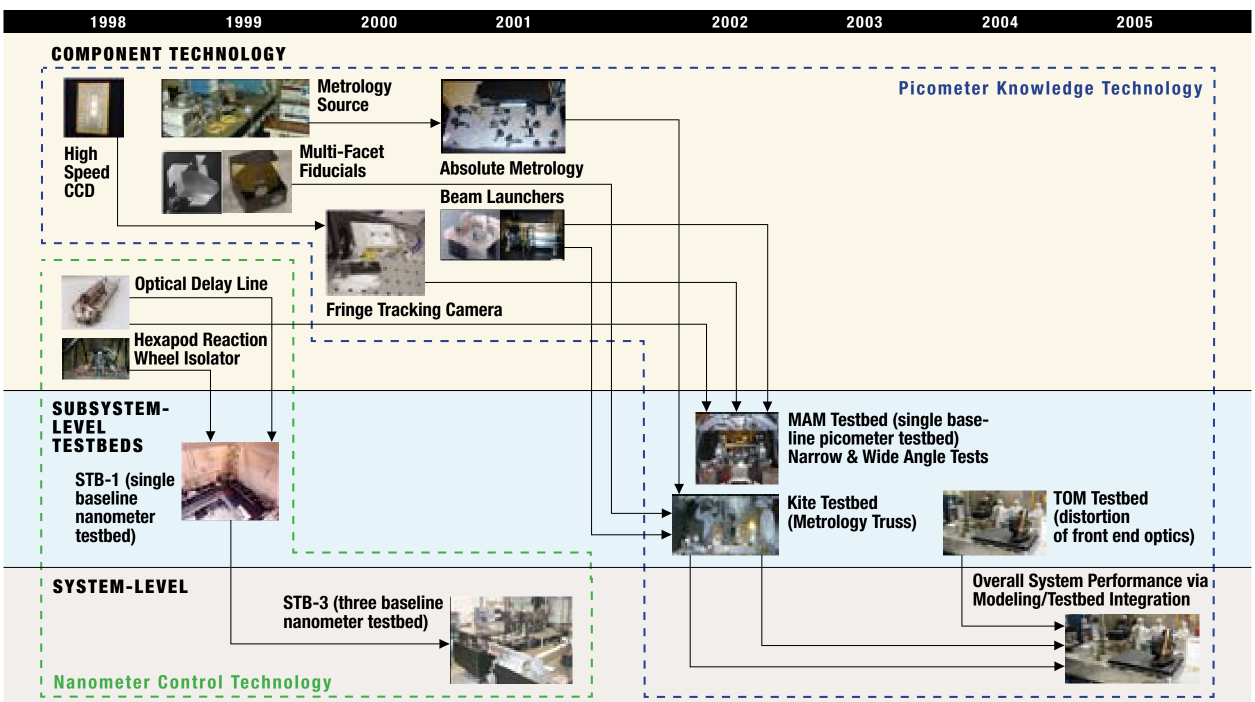


Figure 3–1. *The SIM technology development program has developed all major technology elements to TRL 6 and therefore to readiness for PDR.*

technology program had three parts: (1) detailed error budgets; (2) physical models (testbeds), and (3) detailed numerical models that were required to agree with the physical model (testbed) results within a factor of two. The last system-level activity demonstrated how the instrument picometer knowledge performance verification and validation (V&V) would be accomplished during flight integration and test.

This technology program was so successful that it demonstrated that the full SIM would achieve performance 40% better than the Goal-level performance envisioned by previous Astrophysics Decadal surveys. It was this over-achievement in performance that enabled the simplifications needed for Planet Hunter.

Engineering Risk Reduction Activities

With the completion of the technology program, SIM transitioned into reducing engineering risk. Flight-qualifiable brassboard (BB) versions of the key hardware elements were or are being built, that achieve form, fit and function to the flight designs. Figure 3-2 shows an overview of the BB hardware and how the pieces form the Planet Hunter instrument.

Note that the only three remaining assemblies, shown as CAD models in the figure, are currently under construction (and will be completed and tested before the Fall of 2010). The BB modulating optical mechanism (MOM) is being assembled and will be tested in May 2009, the BB astrometric beam combiner (ABC) is slated to be finished

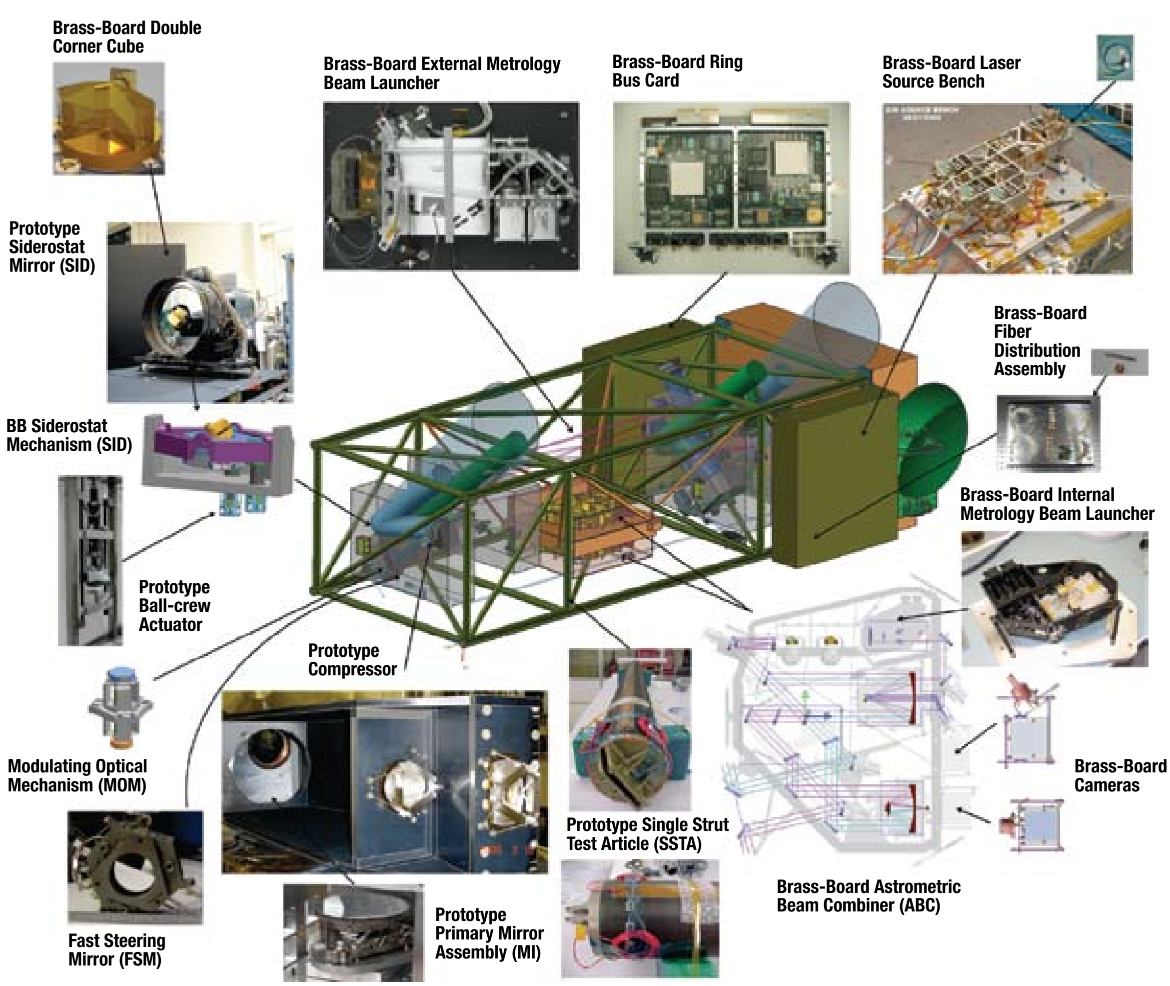


Figure 3–2. *Planet Hunter brassboard hardware that makes up the instrument.*

by the end of 2009, and the BB siderostat by mid-2010. SIM's ongoing development of hardware assemblies into flight-like assemblies continues to show that JPLs standard flight hardware development processes are sufficient for building and testing these assemblies. Currently, there are no significant technical risks to the full-scale deployment of a space-based astrometry mission similar to the Planet Hunter mission. Further information about this technology program can be found in the references below.

Guide-2 Star Tracker

One of the most significant difference between the full SIM and Planet Hunter designs, other than scaling, is the replacement of the Guide-2 Michelson stellar interferometer with an ultra-stable star-tracking telescope (100,000 times more accurate than a typical spacecraft star tracker), called the Guide-2 Telescope. This telescope uses only components that were already developed for SIM. Because of that, we were able to re-use equipment from other testbeds and, in 18 months, develop and demonstrate the needed stability requirement. The performance of 50 μas was achieved in February 2009, and a closeout review is scheduled for April 2009.

Technology Readiness Summary

Planet Hunter, as a variant of SIM Lite, has demonstrated all of the technology and engineering needed for flight by leveraging on the investment in SIM's technology development program. The current funding will complete the entire suite of brassboard hardware, such that every Planet Hunter component will have been vetted for manufacturing, technology and performance risks prior to the end of FY2010. Planet Hunter is technically ready for full-scale development.

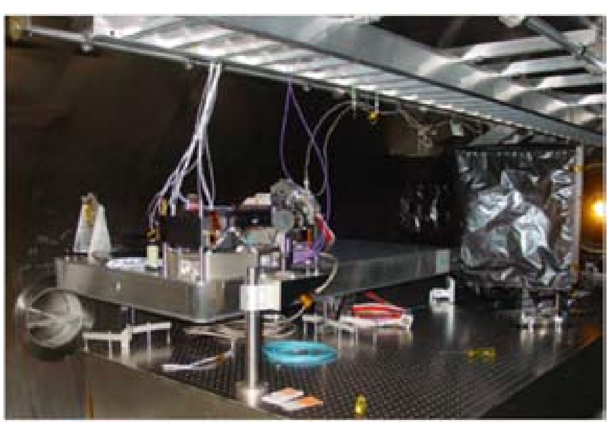
References

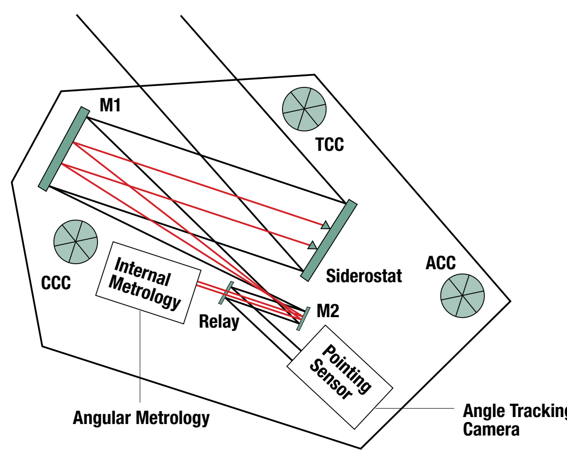
[1] Davidson, J.M. (editor), *SIM Lite Astrometric Observatory: From Earth-Like Planets to Dark Matter*, NASA, January 2009, Theme VI, Section 19.

[2] Marr, J.C, SIM Technology White Paper for the Exoplanets Task Force, Jet Propulsion Laboratory, California Institute of Technology; on the SIM Lite public website at URL: http://planetquest.jpl.nasa.gov/documents/TechExoPTF_Final.pdf.

[3] Laskin, R.A., Successful Completion of SIM-PlanetQuest Technology, SPIE conference on Astronomical Telescopes 2006, also on the SIM Lite public website at URL: http://planetquest.jpl.nasa.gov/documents/SPIE_06-rev6_small.pdf.

Figure 3–3. *The Guide-2 telescope testbed in the vacuum chamber (left). This testbed has demonstrated star-tracking capability at an unprecedented 30 μas level. Diagram of the Guide-2 telescope (right).*





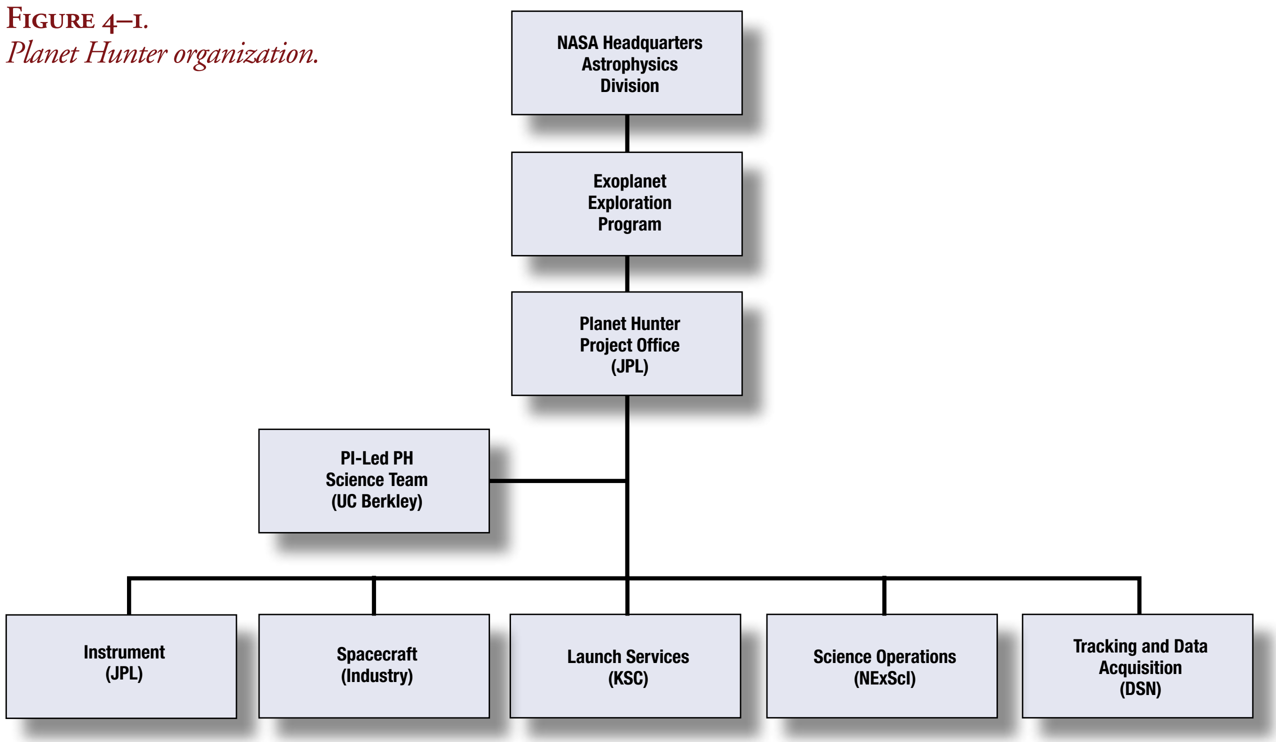
Section 4. Activity Organization, Partnerships and Current Status

Planet Hunter is a large-class planets-only mission concept derived from simplifying the SIM Lite mission funded by NASA as part of the Exoplanet Exploration Program. SIM Lite is currently in late Formulation Phase (Phase B or Preliminary Design) conducting engineering risk reduction activities, building and qualifying brassboard model hardware. Since Planet Hunter is the same as SIM Lite except for relatively minor instrument simplifications, it can be considered to be at the same level of maturity as SIM Lite.

The Planet Hunter's Principal Investigator (Dr. Geoffrey Marcy, UC Berkeley) will lead a science team targeted to consist of the exoplanets subset of the competitively selected SIM science team, which will guide the science performance requirements. The Jet Propulsion Laboratory (JPL) will manage the project, design and build the instrument, and conduct science operations, and industry partners will provide the spacecraft. NASA Kennedy Space Center provides launch services, and the Deep Space Network provides tracking and data acquisition. The NASA Exoplanet Science Institute (NExScI), part of the Astrophysics Data Centers at Caltech, provides science operations, data archival, and analysis tools. The core team, the same as for SIM Lite, has been in place since the SIM project inception in 1997.

The Exoplanet portion of the SIM Lite Science Team, which was selected through the first SIM AO, will continue to conduct the Planet Hunter exoplanet program (which is identical to that of SIM Lite). Together with their Co-I teams, approximately 20 scientists are involved. Approximately 80% of the science observing time of the mission has been assigned to this team. Figure 4-1 shows the Planet Hunter organization.

Figure 4–1.
Planet Hunter organization.



Section 5. Activity Schedule

Planet Hunter is built upon the past Formulation Phase history for the SIM mission that began with Phase A start in October 1997 and Phase B start in July 2003. All the technology work was completed by July 2005 and significant additional engineering risk reduction has occurred since then, as described above in the technology section. Because of this precursor work, we have high confidence in the fidelity of the estimated cost and schedule to go.

An independent cost estimate for Planet Hunter was performed March 2009 by the Aerospace Corporation [1]. At the same time, a JPL–institutional cost estimate was developed by the JPL Engineering Cost Estimating Office using multiple models. Both used a very detailed version of the optimum Planet Hunter schedule described below.

The optimum schedule for the development of Planet Hunter assumes an October 2010 start, launch in July 2015, 30-day post launch IOC (part of Phase D), 120 day science calibration, 5 years of operations, and one year of post operations final data processing, archival, and project closeout. Table 5-1 shows the significant project milestones, their dates, and the years from the start of FY2011.

Schedule Validation

As part of the Aerospace ICE for the SIM Lite mission [2], an Independent Schedule Estimate (ISE) and a complexity based risk assessment (CoBRA) [3] were performed. This tool uses up to 40 parameters to describe the mission and computes a complexity index relative to other missions in the Aerospace CoBRA database. The SIM Lite complexity index and schedule estimates were plotted relative to ~110 other missions in the database (see Figure 5-1).

The points in this plot are: Green-diamond = successful; Yellow-X = impaired; Red-X = failed; gray-diamond = yet to be determined.

Table 5-1. *Schedule.*

Event	Date for a July 2015 Launch	Years from start of FY2011
Start development for launch	*October 2010*	*0*
Mission-level PDR	*October 2011*	*1.0*
Implementation Phase C/D start	*January 2012*	*1.3*
Mission-level CDR	*October 2012*	*2.0*
Observatory I&T (Phase D) start	*June 2014*	*3.7*
Launch Readiness Date (LRD)	*July 2015*	*4.7*
IOC complete; operations (Phase E) start	*August 2015*	*4.8*
Science calibration complete	*December 2015*	*5.3*
5-year science ops complete	*December 2020*	*10.2*
Post-Ops activities complete (Phase F)	*December 2021*	*11.2*

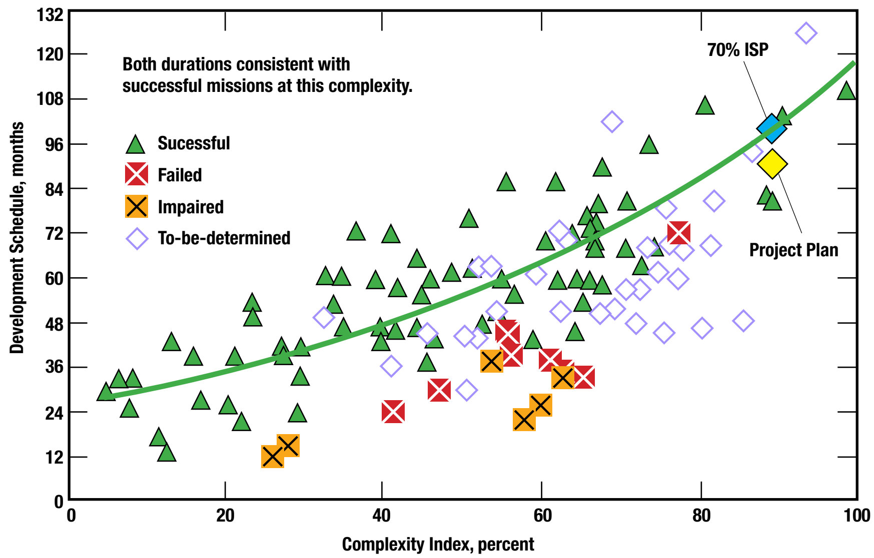


Figure 5–1. SIM Lite schedule estimate. This figure compares the SIM Lite estimated schedule with those of other missions of varying complexity. Planet Hunter would have very similar results – solidly in the range of successful missions of similar complexity.

Since Planet Hunter is a somewhat simpler and somewhat lower cost variant of exactly the same design as SIM Lite, the results from doing a similar CoBRA analysis on Planet Hunter would be expected to be quite similar. The result of this assessment for SIM Lite (see figure) is that both the JPL and 70% Aerospace schedules are consistent with successful missions of similar complexity. Similar results would be expected for Planet Hunter.

References

[1] The Aerospace Corporation, Planet Hunter Independent Cost Estimate, Preliminary Results, March 20, 2009.
[2] The Aerospace Corporation, SIM-Lite Independent Cost, Schedule, and Technical Readiness Evaluation Assessment, NASA HQ Briefing, January 27, 2009.
[3] David A. Bearden, A complexity-based risk assessment of low-cost planetary missions: When is a mission too fast and too cheap?, Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, May 2-5, 2000.

NASA Mission Life Cycle Phase Definitions

Phase A = Concept & Technology Development
Phase B = Preliminary Design & Technology Completion (including long lead procurements)
Phase C = Final Design and Fabrication
Phase D = System Assembly, Integration and Test (I&T), and Launch
Phase E = Operations and Sustainment
Phase F = Closeout

Section 6. Cost Estimate

Planet Hunter is a lower-cost derivative of the deeply studied SIM design. It capitalizes on all of the astrometric instrument technology development, design, and engineering risk reduction activities undertaken over those years for the SIM mission (12.5 years and $590M RY$ invested to date). Having built and tested brassboards (form, fit, function) of most of the critical hardware assemblies for Planet Hunter under the prior SIM funding, the fidelity of the Planet Hunter cost estimate provided here is very high.

Planet Hunter Cost Estimate Methodology

An independent cost estimate for Planet Hunter was performed during March 2009 by Aerospace Corporation [1] under contract to the JPL Engineering Cost Estimating Office and consisted of an update to the SIM Lite ICE completed in January 2009. At the same time, a JPL institutional cost estimate was developed. A very detailed Cost Analysis Data Requirements (CADRe) document, which provides detailed data defining the mission to be developed, was prepared by the SIM Lite Project in October 2008, modified to reflect the Planet Hunter changes, and used as input to a broad suite of cost estimating methods at both Aerospace and JPL.

JPL estimating methods used included a JPL Team X estimate and an array of estimates from the JPL's Engineering Cost Estimating Office, using the SEER, PRICE, and PMCM cost models. The Aerospace Corporation, using the same CADRe, also used a broad array of estimating methods, including SEER, PRICE, MICM, Analogy, USCM8, and NAFCOM 2006.

The JPL institutional estimate resulted from averaging the several separate JPL estimates. Similarly, the Aerospace ICE estimate was derived as an average of the several Aerospace estimates. Both estimates were completed in March 2009.

These estimates were performed using a much more detailed version of the schedule described in the previous section, namely, an October 2010 development start date with launch in July 2015, followed by 1 month of on-orbit checkout (included in Phase D), 4 months of calibration, 5 years of operations, and 1 year of final data processing, data archive, and project shutdown.

Planet Hunter uses only technology from the successful SIM technology development program completed in 2005. No technology funding is included in the cost estimates below.

There are no current domestic or international collaborations for Planet Hunter. The cost estimates quoted below are for a Planet Hunter entirely funded by NASA.

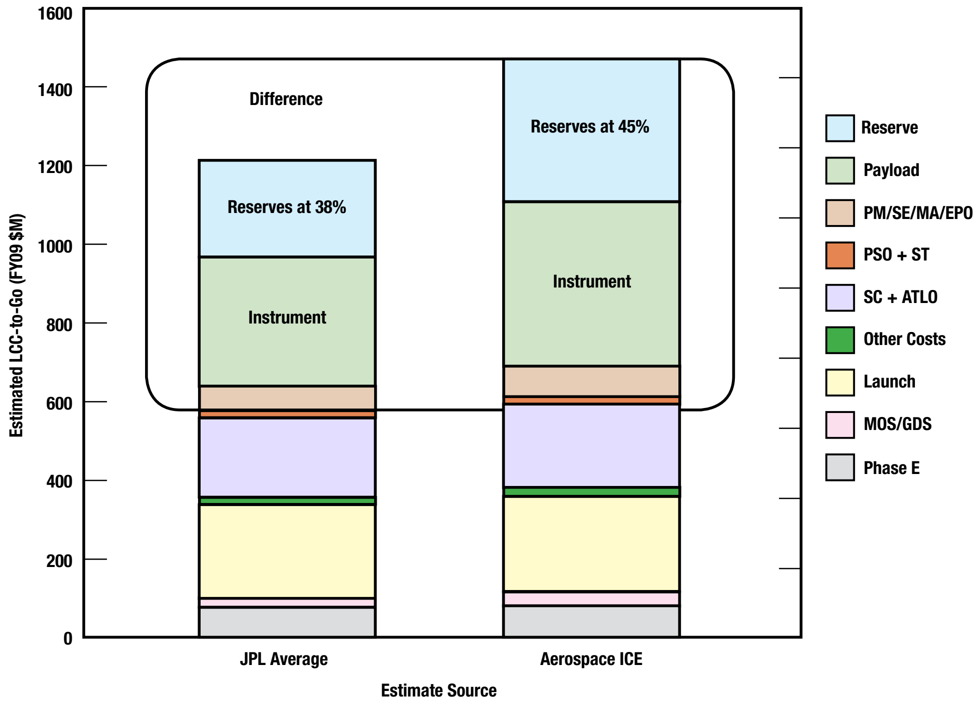
Planet Hunter Cost Estimate Preliminary Results

Phases BCD — Development cost-to-go (less launch costs) include the JPL institutional estimate (average of the JPL estimates) of $900M FY09$, and the Aerospace ICE estimate of $1,150M FY09$. Both estimates are at the 70% confidence level on the cost confidence curves generated by the respective organizations (Figuare 6-1).

The differences between the JPL institutional and Aerospace ICE estimates are largely in the instrument and the budget reserves required to achieve 70% cost confidence. The Aerospace instrument estimate is $420M FY09$, which is ~30% higher than the JPL instrument estimate of $330M FY09$. Similarly, the Aerospace budget reserves of $350M FY09$ are ~45% higher than the JPL budget reserves of $240M FY09$, part of which is reserve on the delta in instrument cost and part from the higher recommended reserve percentage of 45% (vs. JPL's 38%). This diversity is not surprising given the first-of-a-kind nature of the instrument.

The Aerospace project management, project system engineering, and mission assurance costs (PM/PSE/MA) of $83M FY09$, being a wrap on other costs, are also higher than the corresponding JPL

Figure 6–1. *Comparison of Planet Hunter and ICE estimated costs. The estimates differ in the projected costs of the instrument and the required reserves.*



estimate ($64M FY09$) by 30%. Other project element costs are roughly the same between the two estimates.

The higher Aerospace recommended reserve percentage (45% vs. JPL 38%) derives from the slightly more conservative (than the JPL Engineering Cost Estimating Office) cost risk analysis assumptions used to generate the Aerospace cost risk analysis S-curve.

A cost for launch services was developed by NASA's Launch Services Program office in March 2009. Based upon SIM Lite's launch requirements, a launch services cost estimate range of $210M FY09$ to $270M FY09$ was submitted to SMD. Since Planet Hunter uses the same LV, the average value of $240M FY09$ was used above and in Table 6-1.

Phase EF — Operations and Closeout: The cost estimates for 5.3 years of operations and one year of post-operations data processing, data archive, and project closeout range from $77M (Aerospace ICE) to $76M (JPL Institutional), both in FY09$.

Science Community Funding: Based on the JPL institutional estimate, the science community would receive approximately 1/3 (~$4M FY09$) of the development science budget and 1/3 (~$20M FY09$) of the operations phase budget, for a total of ~$24M FY09$.

Table 6-1 summarizes the Aerospace and JPL estimates.

Table 6–1. *Planet Hunter cost in constant year FY09$ at 70% confidence.*

Estimate Range	Phase BCD	LV	Phases EF	LCC-to-Go
JPL Institutional	*$900 M**	*$240 M*	*$76 M****	*$1,210 M*
Aerospace ICE	*$1,140 M***	*$240 M*	*$77 M****	*$1,460 M*

Schedule durations: B-15 mo.; CD=43 mo.; EF=72 mo. Phase definitions are at the end of this section. * Includes 38% reserves. **Includes 44% reserves. BCD cost breakout into Phase B and Phase CD was not provided. ***Includes 15% EF reserves.

Planet Hunter Cost Estimate Validation

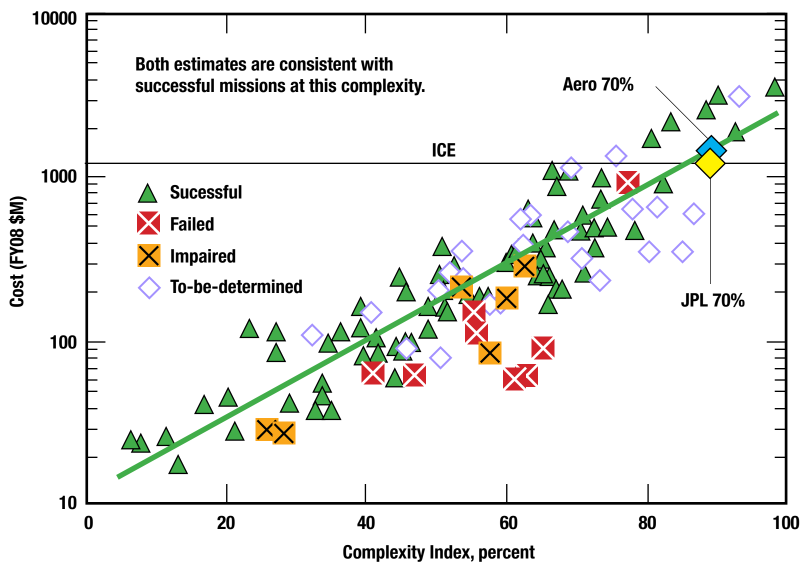
In addition to the model and analogy–based independent cost estimate performed by the Aerospace Corporation, for SIM Lite Aerospace also checked the cost validity using a tool called Complexity Based Risk Analysis (CoBRA) [2][3]. A similar analysis was not done for Planet Hunter due to its similarity to SIM Lite. The CoBRA tool uses up to 40 parameters to describe the mission and computes a complexity index relative to other missions in the Aerospace CoBRA database. The SIM Lite complexity index and cost was then plotted relative to ~110 other missions in the database (see Figure 6-2).

The points in this plot are: Green-diamond = successful; Yellow-X = impaired; Red-X = failed; gray-diamond = yet to be determined.

The plot suggested that SIM Lite costs estimates, by both JPL and Aerospace, are consistent with other successful missions of similar complexity.

Planet Hunter would have a slightly lower complexity index and has a somewhat lower cost, so would plot a little to the left and downward from the SIM Lite position plotted above, but still solidly in the range of successful missions.

Figure 6–2. *SIM Lite cost estimate. This figure compares the SIM Lite estimated cost with those of other missions of varying complexity. Planet Hunter would have very similar results – solidly in the range of successful missions of similar complexity.*



References

[1] The Aerospace Corporation, Planet Hunter Independent Cost Estimate, Preliminary Results, March 20, 2009.
[2] The Aerospace Corporation, SIM-Lite Independent Cost, Schedule, and Technical Readiness Evaluation Assessment, NASA HQ Briefing, January 27, 2009.
[3] David A. Bearden, A complexity-based risk assessment of low-cost planetary missions: When is a mission too fast and too cheap?, Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, May 2–5, 2000.

NASA Mission Life Cycle Phase Definitions

Phase A = Concept & Technology Development
Phase B = Preliminary Design & Technology Completion (including long lead procurements)
Phase C = Final Design and Fabrication
Phase D = System Assembly, Integration and Test (I&T), and Launch
Phase E = Operations and Sustainment
Phase F = Closeout

The work described in this report was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The cost estimates summarized in this document do not constitute an implementation-cost commitment on the part of JPL or Caltech.