SIM-PlanetQuest: Progress Report

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ABSTRACT

SIM-PlanetQuest is a NASA astrophysics mission that is implementing the National Research Counsel's recommended Astrometric Interferometry Mission (AIM) to develop the first, in-space, optical, long-baseline Michelson Stellar Interferometer for performing micro-arcsecond-level astrometry. This level of astrometric precision will enable characterization of planetary systems around nearby stars and enable a number of key investigations in astrophysics including calibration of the cosmological distance scale, stellar and galactic structure and evolution, and dark matter/energy distribution. This paper provides an update on the SIM-PlanetQuest Mission covering the results of the 2005 mission redesign and the recent completion of the last in a series of technology "gates". The SIM-PlanetQuest mission redesign was directed by NASA to recover eroded mass and power margins and to meet specific implementation cost targets. The resulting mission redesign met all redesign objectives with minimal impact to mission science performance. This paper provides the mission redesign objectives and describes the resulting mission and system design including changes in science capability. SIM-PlanetQuest also completed the last of eight major technology development gates that were established in 2001 by NASA, completing the enabling technology development. The technology development program, the last gate, and its significance to the project's flight verification and validation (V&V) approach are briefly described (covered in more detail in a separate paper at this conference). An update on project programmatic status and plans is also provided.

Keywords: Interferometer, Interferometry, astrometry, SIM, PlanetQuest, exo-planets, planet-finding

1. INTRODUCTION

The SIM PlanetQuest mission (formerly known as the Space Interferometry Mission, and hereafter referred to simply as SIM, resulted from the 1991 recommendation of the U.S. National Research Council's (NRC) Astronomy and Astrophysics Survey Committee (AASC)[1] that the U.S. National Aeronautics and Space Administration (NASA) undertake an Astrometric Interferometry Mission (AIM) that would employ the then recently developed, and still evolving, techniques for ground-based, optical, long-baseline interferometers in a space mission that would extend the performance into the few micro-arcsecond (μas) regime by eliminating the effects of Earth's atmospheric disturbance. The NRC envisioned a broad array of scientific objectives, including a broad astrophysics program and characterization of extra-solar planetary systems, and the demonstration of technologies needed to enable future very large space-based telescopes by breaking the linkage between resolving power and aperture size.

Figure 1: SIM-PlanetQuest Flight System

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The NRC's AIM mission was renamed the SIM in late 1996 following a NASA selection from competing design concepts and project management was assigned to the Jet Propulsion Laboratory (JPL) in Pasadena, California. SIM was later renamed SIM-PlanetQuest in 2005 to emphasize SIM's role in exo-solar planetary system characterization. The NRC's AASC again endorsed the mission in its 2001 Decadal report[2], refining the objectives slightly and shifting additional focus to the characterization of extra-solar planetary systems due to the increasingly frequent discovery of large planets using ground-based radial-velocity, photometric, and other techniques. SIM's scientific capabilities cited were: *"...[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."* The report also emphasized the dual capability of SIM, noting that this capability would enable *"...both narrow-angle astrometry for detecting planets and wide-angle astrometry for mapping the structure of the Milky Way and other nearby galaxies."*

The NRC AASC's Panel on Ultraviolet, Optical and Infrared Astronomy (UVIOR Panel)[3] stressed that "the primary scientific objective of the SIM mission is ultrahigh-accuracy astrometry." SIM's capabilities for making distance measurements of "*1 percent accuracy to distances of several kiloparsecs and of 10 percent accuracy throughout the Galaxy*" would address the astrophysical goals of "*providing a firm foundation for the understanding of stellar astrophysics ... [making] luminosity determinations for key classes of stars ... [to] reduce the calibration uncertainties in the cosmological distance scale ... [and refining] our knowledge of the distribution of dark matter.*" The UVOIR Panel stated that *"[s]earching for planets near stars in the solar neighborhood is the most ambitious of SIM's goals ... [because the search] should generate a preliminary survey of the local planetary population and a more extensive survey of the Jovian-mass planets ... and ... [thereby] not leave any ambiguity about the masses of extrasolar planets."*

The search for extra solar planets was further endorsed in 2004 as a key element of the U.S. President's Vision for Space Exploration (VSE)[6] which included the objective: "*Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars*".

In January 2005, the project was directed by NASA to undertake a mission redesign to address eroding mass margin (relative to the launch vehicle capability) and increased estimated mission cost. The project was requested to provide at least two possible design options to meet two different development cost targets and was allowed that all top level requirements would be open to revision in order to meet the cost targets. In July 2005, the project presented NASA with the mission redesign results, presenting two options, one meeting each of the two cost targets given to the project that differed from one another primarily in the size of the collecting aperture (one at 75% of pre-redesign collecting area and one at 50% of pre-redesign collecting area). Following the mission redesign presentation to NASA, the project was directed to continue the development of the larger collecting area option. With the exception of slightly longer integration times resulting from the smaller collecting aperture, there was little other overall impact to mission science capability, with predicted capability remaining very close to the mission capability goals.

2. ASTROMETRIC MEASUREMENT CAPABILITY

SIM measures the position and proper motions of stars in one of two observing modes: Narrow Angle (NA) or Wide Angle (WA).

The NA mode is probably the easiest to understand in that in this mode SIM measures the position of a target star relative to nearby reference stars (four or more) that are within about 1° of the target star by 'chopping' between them to measure their relative positions over time. The NA mode is the more accurate of the two modes enabling accuracy to about 1 μas.

Science Observation	Target Magnitude	Minimum Performance	Baseline/Full Performance	Goal* Performance
Nearby Stars	7 mag	3 μas	3 μas	1.09 μas
Grid Stars	10.6 mag	10 μas	10 μas	3.35 μas
Legacy NA	10 mag	3 μas	3 μas	1.37 μas
Legacy WA	18 mag	30 μas	10 μas	4.89 μas
Faint NA	13 mag	N/A	N/A	2.87 μas
Faint WA	19 mag	N/A	N/A	35.0 μas

* Goal performance is protected by 30% margins in the design point allocations.

Table-1: SIM-PlanetQuest Performance

NA observations are made by sequentially alternating (chopping) between a target star and a number of nearby surrounding reference stars located within about 1-degree of the target star. This chopping removes instrument drifts, enabling the most accurate performance from the SIM

instrument. A single set of target/reference-star measurements (on the order of 10 chops between the target and the set of reference stars) is called a single NA observation and represents a stand-alone measurement. Accuracy achieved will depend upon star brightness (see Table 1).

The WA mode measures the position of stars ultimately relative to a set of distant quasars. This is done by collecting the positions of target stars measured relative to each other within each of about 1,300 overlapping 15° tiles that cover the entire sky, with each tile being visited repeatedly over the full 5-year mission. The positions of all of the stars and some instrument parameters are then solved for all at once, producing stellar positions accurate to between 4 μas and 30 μas, depending upon the star brightness and the length of integration time on that object. A subset of the observed WA stars called Grid Stars are of magnitude 10.6 or brighter mostly K-giants whose positions will be determined to an accuracy of better than 4 μas and will serve as a full-sky optical reference grid that will be tied to the International Celestial Reference Frame (ICRF).

WA observations are made over the instrument's entire fifteen-degree field-of-regard (FOR) and consist of a single measurement of each star's position. Since measurements of stars within the FOR (about 50 of them) occur over about a 1-hour period, there are larger errors in WA measurements than for NA measurements.

SIM-PlanetQuest's astrometric measurement accuracy specified at three levels: Minimum (the worst it can be before reconsideration of the mission occurs), Baseline/Full (the required performance from NASA's perspective), Goal (the desired capability of the system, from which the SIM project's current design point is derived). NA and WA Minimum and Baseline performance are independent of stellar brightness but goal performance is not. Table-1 shows these SIM-PlanetQuest performance objectives for various target star brightnesses. The Legacy NA and Legacy WA numbers compare to pre-redesign Goals of 1.0 uas and 4.0 uas, respectively, with the new values resulting from a slightly shorter post-redesign instrument baseline (9 m vs prior 10 m).

3. SCIENCE: PLANET FINDING

The NASA's Science and Mission Directorate (SMD) has been developing a number of missions that will contribute to characterization of proto-planetary discs, planetary systems and planets themselves. None of these missions tell the whole story by themselves. Each mission provides pieces of the puzzle that will enable assembling solid understanding of how planetary systems form, their distribution, their characteristics and whether any harbor Earth-like planets (considered to be rocky planets in the range 0.5 to 10 Earth masses) in their habitable zones (where liquid water can exist, considered to be 0.75 to 1.5 AU but scaled with star brightness, see Catanzarite, el al[8]), that are about the same density as our rocky planets so that they have a solid surface (giving diameters of about 0.5 to 2 times the diameter of the Earth), that are far enough away from their parent star to avoid tidal lock, and that actually exhibit characteristics that we would recognize as indicating the presence of biological activity. Additionally, we would like to know that there are gas giants in these same systems much further away (ala Jupiter) that can sweep out comets sufficiently to allow life to evolve on the Earth-like planet(s) in these systems.

The Kepler[7] 4-year mission, currently slated for launch in 2008, will characterize the frequency of occurrence of rocky planets in inner orbits around about 100,000 14th magnitude or brighter dwarf stars lying in a 12 degree field of view pointed in the direction of the Cygnus constellation. Kepler uses the transit method whereby the light intensity from a star dips during the transit of a planet (requiring, of course, that the planetary system by oriented in such a way that the planets cross the line of site between the star and Kepler, estimated to be ~0.5% to ~1%). Most of the stars that Kepler will observe are very distant (out to about 3000 light years, ly) compared to the stars that SIM will characterize (out to ~100 ly). If such planets are very common, Kepler should find something like a few hundred rocky planets.

What Kepler primarily does is to answer the currently unknown fundamental question as to the relative frequency of occurrence of rocky planets around dwarf stars (like our Sun). Kepler's results will be used to tailor SIM's planet observing program. Should Kepler show that rocky planets be rare, SIM will use its planetary discovery time to survey a greater number of nearby stars (~250) for larger rocky planets in habitable zones. Should rocky planets be common, SIM will survey fewer stars (in the range 60 to 120) but will search deeper for smaller planets. SIM will survey the best candidates for planetary systems within 30 pc and will be able to detect planets of all sizes around all of those surveyed, returning orbital parameters and mass [see Catanzarite, et al].

In addition for looking for close-by inner orbit rocky planets, SIM will characterize the planetary architecture of some 2,000 stars by looking for planets in the range from Uranus (14 Earth masses) to Jupiters (318 Earth masses).
Unlike Kepler, SIM will be able to detect planets around every star that has them, regardless of the orientation of the planetary disk. Also unlike Kepler, SIM will determine the mass of any planets discovered and, in fact, is the only NASA mission capable of determining planetary mass, the most fundamental property of a planet and one that is key to the existence and characteristics of the planet's atmosphere. Also unlike Kepler, all planets discovered by SIM will be close enough that they will be candidates for direct planet observation by missions such as the Terrestrial Planet Finders (TPFs)[4] (TPF-C for reflection spectrum and TPF-I for emission spectrum) or later Terrestrial Planet Imagers (TPIs).

SIM planet finding science programs will consume about one-third of SIM's total Science observing time. Of the planet-finding program time, about half has already been allocated to the three Key Projects already selected. Details of all of the investigations already selected can be found on the SIM-PlanetQuest website [Ref TBD]. The remaining time will be allocated through competitive proposal calls about the time that SIM enters full scale development (Phase C/D, in the NASA lifecycle).

4. SCIENCE: ASTROPHYSICS PROGRAM

The remaining approximately two-thirds of SIM science mission time is used for astrophysics objectives that can be accomplished with SIM's precision astrometric capabilities, the primary reason for the original NRC recommendation that NASA undertake the precision astrometry mission that has become SIM. While astrometry is one of the oldest of sciences, the precision offered from a space advantage opens vast new horizons for science based upon accurate measurements of stellar size, mass, distance and motion. SIM's science program aims to take advantage of SIM's micro-arcsecond class measurements to open these vistas using both of SIM's observing modes (WA and NA).

About half of SIM's astrophysics science observing time has been allocated to a set of seven astrophysics Key-Projects and the observing programs of five Mission Scientists, all of whom were competitively selected by NASA. The details of each of these programs can be found on the SIM-PlanetQuest website[10] that has both summaries of their programs and their full proposals. These programs were selected early in the development of SIM to enable the teams to accomplish preparatory science that includes radial velocity pre-screening of candidate objects and to perform fundamental research that will enable teams to better plan their observing and data reduction programs.

The projects of the current science team will contribute to areas such as: How did the galaxy form and how is it evolving now?; What are the masses and mass distributions of nearby galaxies?; What is the nature of dark galactic matter?; How old are the oldest stars in the galaxy?; What are the masses of the stars?; What is the rotation of our local apparent standard of rest?; How do optical and radio images register at the smallest angular scale?; What is the origin, structure, and evolution of the 'central engines' in the nuclei of quasars and active galaxies (AGNs)?.

Future solicitations will address three additional categories of projects that have been identified to date: General Observer (GO), Legacy and Archival Research. General Observer (GO) programs are for smaller projects that do not require significant preparatory science and are usually for one or two years in duration. Legacy programs are programs that will have lasting scientific value. Archival Research proposals are proposals that will utilize archived data (after a proprietary period has expired) to address other scientific questions that may be mined from that data.

Outside of the science observation time allocations, the project will also undertake WA observations of stars from a set of approximately 1300 (mostly K-giant at distances of ~1kpc) Grid Stars distributed roughly uniformly over the entire sky that will be used to develop a quasar-anchored reference grid of stars whose positions are known to an accuracy of better than 10 μas (goal 3.4 μas). These will be related to the International Celestial Reference Frame (ICRF), a primarily radio frequency frame, for use by future astrophysics missions.

All science observing time (planets and astrophysics alike) for the second 5-years of mission life (Goal mission), should that be obtained, will be open for competitive selection.

Further information about SIM's research opportunities is available on the SIM-PlanetQuest web site[10].

5. INTERFEROMETER TUTORIAL

Interferometers are a form of sparse aperture telescope and can combine light from multiple telescopes in either an image plane (Fiseau), forming an image, or in a pupil plane (Michelson), forming (for point sources like stars) a white light interference fringe. SIM-PlanetQuest is a Michelson interferometer operating in the visible portion of the spectrum (400 to 1000 nm). The advantage of a pupil plane interferometer over a filled-aperture telescope is higher resolution but this is at the expense of field of view and fewer photons collected per unit time (which isn't a problem if looking at relatively bright objects).

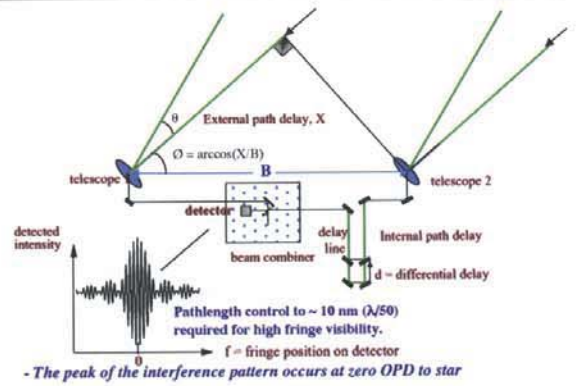

Figure 2: A Single Interferometer "Sensor"

Figure 2 shows a single interferometer "sensor", consisting of two collector telescopes separated by a baseline, B, a delay line and a beam combiner. Light from a star (*not* located at right angles to the baseline, B) arrives at the further collector telescope slightly later than its arrival time at the nearer collector telescope resulting in an external (or geometric) optical path delay (OPD). Optics route the light from the two collector telescopes back to the beam combiner, inserting in the nearer telescope leg an internal optical delay equal to the external delay in the other leg, resulting in the optical path lengths being matched to within a few nanometers. Internal laser metrology is used to measure the inserted internal optical delay as an analog for the external geometric optical delay.

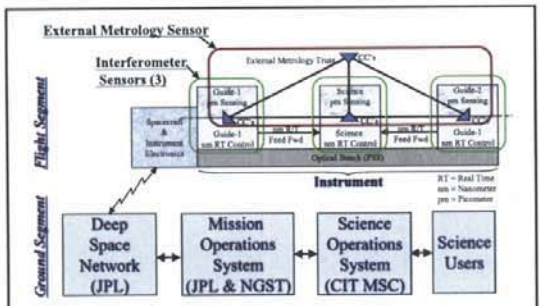

Figure 3: SIM Building Blocks

Assuming that one can determine the length and orientation of the interferometer baseline, B, then one can solve for the angle of the incoming stellar wavefront. Much of SIM-PlanetQuest's complexity revolves around determining these parameters. In practice on SIM-PlanetQuest, angles are measured between closely spaced stars by alternating (chopping) between these stars relatively quickly in order to remove system drifts.

6. SYSTEM CONFIGURATION

Figure 3 shows the building blocks of the SIM-PlanetQuest system. The flight segment consists of one large facility-class instrument, a 3-axis stabilized spacecraft, a launch vehicle and a launch vehicle adapter. The ground segment consists of the Deep Space Network, a Mission Operations System and a Science Operations System (the launch vehicle ground control system is considered part of the launch vehicle).

6.1 Instrument

The SIM-PlanetQuest instrument consists of three visible-wavelength Michelson (pupil plane) stellar interferometer sensors (each like Figure 2) and one external metrology sensor, all supported by a Precision Structure subsystem (PSS) and controlled by the Real-Time Control (RTC) subsystem. Instrument layout is shown in Figure-4.

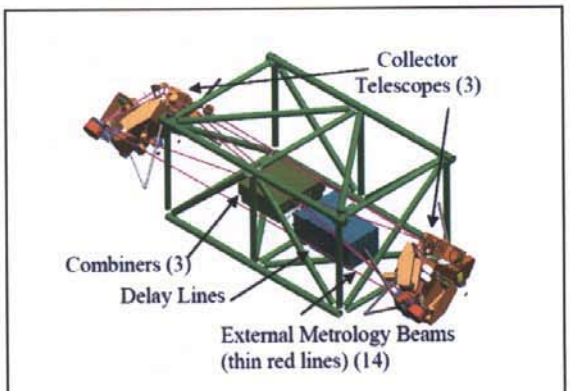

Figure 4: SIM Instrument Layout

One of the three Michelson stellar interferometers has a baseline of 9 meters and serves as the Science interferometer. The other

two interferometers have a somewhat shorter baseline (7.2 m) and serve as Guide interferometers (essentially forming a micro-arcsecond two-axis star tracker) to stabilize the line of sight of the Science interferometer. The Guides track relative bright stars at opposite edges of the field of regard (FOR), generating stabilizing feed forward control information for the science interferometer (to enable making science measurements on dim stars down to visual magnitude 19 in brightness) as well as feeding precision attitude information to the spacecraft attitude control system to reduce the size of the ACS dead-band and thus reduce beam-walk on the instrument optics.

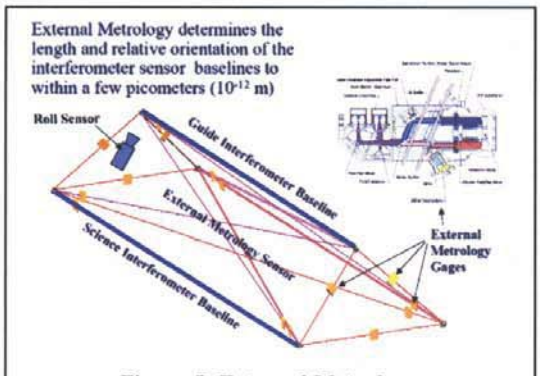

Figure 5: External Metrology

The External Metrology sensor shown in Figures-4 &-5 is a laser truss that measures the baseline length and relative orientation of the three interferometers. The truss consists of fourteen laser beams launched by fourteen metrology gauges that are each capable of measuring the distance between optical corner cube fiducials to an accuracy of a few picometers. This truss is used in non-real-time to reconstruct on the ground where the optical elements were located relative to each other as a function of time, correlated to science measurements.

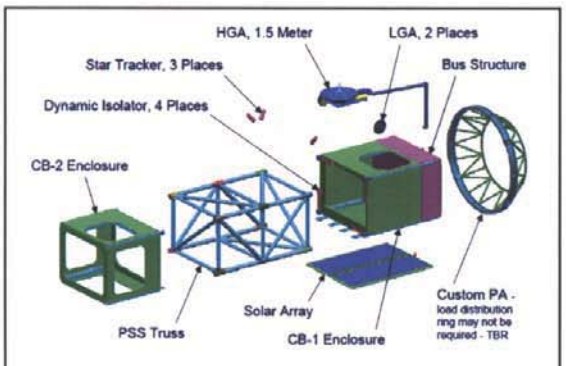

Figure 6: Structural Layout

The Precision Structure subsystem (PSS) is a composite truss structure that supports the components of the interferometer and the collector bay enclosures as shown in Figures-4 and -6. Instrument optical elements (collector telescopes, delay lines and combiners) are connected to the PSS via support struts. Thermal radiators are mounted on the top surface of the PSS that is always facing away from the sun (the top surface of the PSS is a sun exclusion zone). Thermal control for the PSS is provided by the Spacecraft. Vibration isolation between the spacecraft and the PSS is provided by four passive viso-elastic dynamic vibration isolators shown in Figure-6.

The Real Time Control (RTC) subsystem is physically mounted in the Spacecraft bus structure and contains three RAD 750 flight computers, and associated electronics to control the entire instrument. Intra-instrument communications is handled via a modified SpaceWire (IEEE 1393) ring bus.

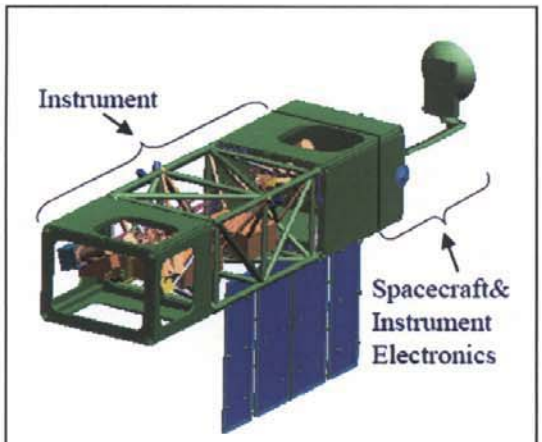

Figure 7: Deployed Flight Segment

6.2 Spacecraft

The SIM-PlanetQuest spacecraft is a generic spacecraft suitable for a deep space mission and is mounted to one of the collector bay enclosures inside of a bus structure (Figure-6) that also encloses a portion of the instrument electronics. The spacecraft provides a KA-band telecom system, 6-kw GaAs solar array, 512 Gbit solid state recorder, six vibration-isolated reaction wheels, a monoprop momentum unloading system, thermal control and provides the mounting point for the launch vehicle adaptor.

6.3 Flight Segment Configuration

The full spacecraft-instrument configuration is shown fully deployed in figure-7.

6.4 Launch Vehicle

SIM-PlanetQuest will launch on either an Atlas V 551 or a Delta IV Heavy launch vehicle from the Kennedy space center, Cape Canaveral, Florida, USA. Figure-8 shows the flight segment packaged for launch in a 5m x 19m "long" faring suitable for either of these two vehicles. Selection of the particular vehicle will be made at the start of full-scale development.

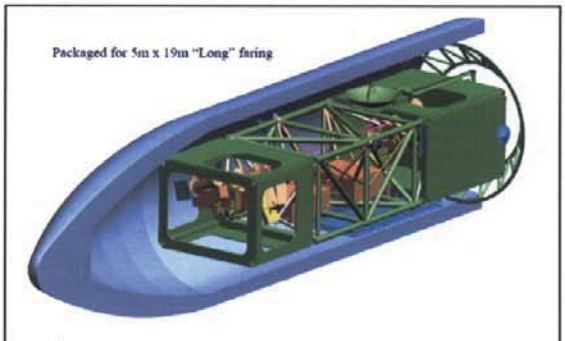

Figure 8: Packaged for Launch

6.5 Mission Operations System

SIM-PlanetQuest will utilize the NASA Deep Space Network (DSN) and Advanced Multi-Mission Operations System (AMMOS) services as the base for the project mission operations system. The SIM-PlanetQuest spacecraft will be operated by Northrop Grumman Space Technologies (NGST) from their Redondo Beach, CA, facility and the Instrument will be operated from the Jet Propulsion Laboratory (JPL) in Pasadena, CA.

6.6 Science Operations System

Science operations will be coordinated by the SIM-PlanetQuest Science Operations System (SOS) located at the Michelson Science Center (MSC) on the campus of the California Institute of Technology (CIT) in Pasadena, CA, USA. The SOS will provide the primary interface to the science user community and will provide uplink observation planning and downlink science data processing and distribution functions. Additionally, the SOS will coordinate science user proposal calls and selections.

6.7 Integration Sequence

Figure-9 shows the assembly sequence for the flight segment. The instrument system subsystems are assembled at the Jet Propulsion Laboratory (JPL) in Pasadena, California, USA, where functional testing in air will be completed. The instrument will then be shipped to Northrop Grumman Space Technology (NGST) in Redondo Beach, CA, USA, where it will be performance tested in vacuum. The spacecraft will also be separately functionally and performance tested at NGST prior to mate with the instrument for final testing prior to ship to Cape Canaveral, Florida, USA for launch operations.

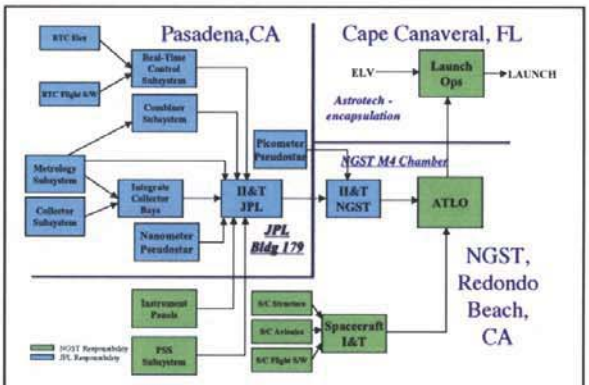

Figure 9: Integration Flow

7. TECHNOLOGY COMPLETION

The SIM-PlanetQuest technology development program has been underway for the better part of a decade. Eight technology Gates (Figure-10), taken from the full SIM technology development plan, were established in 2001 by NASA 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) of six (out of nine levels) has been reached, signifying readiness to proceed to flight hardware development.

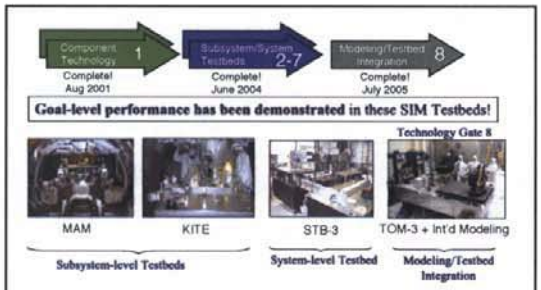

Figure 10: Technology Completion

These eight Technology Gates spanned the range from component technologies to system level technologies that demonstrate not only system performance in relevant environments but also demonstrates the methodology that will be used to test and demonstrate performance of the flight system.

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

The last of these Technology Gates was key in that it demonstrated the integration of specific test data into an overall model of the instrument and mission to predict overall mission performance, demonstrating the methodology to be followed during the full flight system integration and test. Work in support of this technology gate also demonstrated that the instrument 'sensors' (the three single interferometer sensors or the external metrology sensor) can be performance tested separately (i.e., they do not interfere with each other) and the results combined via models, verifying the viability of this approach for flight instrument performance verification.

Completion of the full SIM technology development program was formally signed-off by NASA in March 2003 following extensive review of all technology program objectives and their status by three external review teams.

8. SCIENCE OPERATIONS

SIM-PlanetQuest will be launched into an Earth-Trailing Heliocentric Orbit (ETHO) that takes the system away from the time varying thermal influence of the Earth. The orbit selected is slightly more elliptical than Earth's orbit resulting in a gradually increasing distance (~0.1 AU/year), looping apparent distance

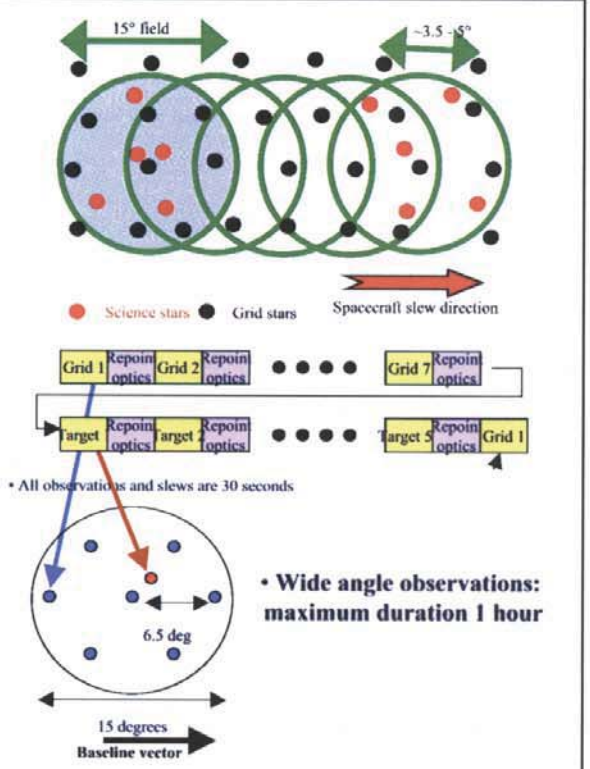

Figure 12: Wide Angle Observing Scenario

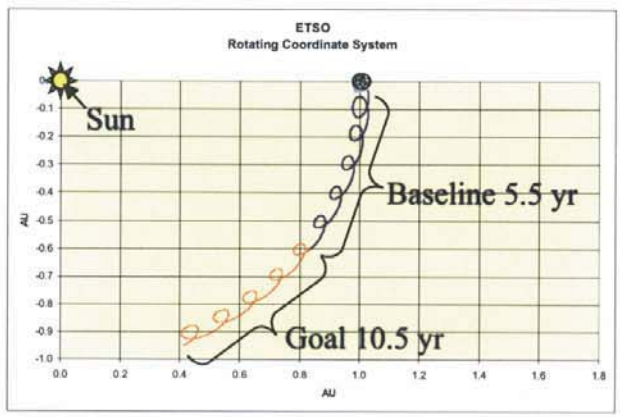

Figure 13: SIM-PlanetQuest Drift-Away ETHO

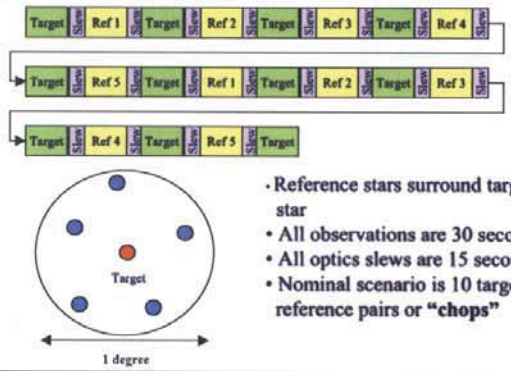

Figure 11: Narrow Angle Observing Scenario

between SIM and the Earth (Figure 11). This increasing distance from Earth with mission time results in increasing coverage requirements from the NASA Deep Space Network (DSN) as the mission progresses, being driven during the early mission by velocity determination requirements but later by the demands of maintaining telecom downlink volumes as the Earth-spacecraft distance increases during the mission.

SIM-PlanetQuest observes the sky in 15° 'field of regard' (FOR) 'tiles' (about 1,300 of them) that are obtained by positioning the spacecraft orientation until the two Guide interferometers have acquired their guide stars and then using the science interferometer's siderostat (moveable telescope mirror) to observe targets anywhere in the full 15° FOR. During each tile, various types of targets might be observed, including Grid stars, WA targets and NA targets. A typical tile takes about an hour. Subsequent tiles overlap previous tiles by roughly half so that one or more identical Grid stars can be observed for each tile orientation, providing the means to tie the tiles together. Over a relatively short time, each target within a tile needs to be observed with the instrument in roughly orthogonal orientations in order to obtain a two dimensional position for the object. Observing scenarios for both WA and NA targets are shown in Figures 12 and 13.

9. PROJECT STATUS

9.1 Mission Redesign

In January 2005, NASA directed the project to redesign the mission to meet specific cost targets and to restore margins that had become eroded due to changing launch vehicles from the ill-fated Columbia space shuttle to an expendable launch vehicle. This mission redesign was completed in July 2005 with a report to the NASA Science and Mission Directorate (SMD), meeting all requirements of the mission redesign with little overall impact to project science and with a design that did not require any new technology development.

Changes that were made during the mission redesign included: reduction in the science interferometer baseline length from 10m to 9m; reduction in the size of the science interferometer telescope to 75% of its pre-redesign collecting area; and elimination of the spare science interferometer which had been carried for redundancy, resulting in meeting redundancy requirements at lower levels of the design. These changes had the net effect of reducing the predicted design point performance slightly (WA from 4 μas to 4.9 μas; NA from 1 μas to 1.4 μas). For Grid stars (using stars brighter than 10.6^{th} magnitude) and Planet-finding (using stars brighter than 7th magnitude) the overall performance essentially unchanged from pre redesign performance. The revised performance is still factors of several better than that requested by the NRC in their two decadal reports (see the introduction).

9.2 Development Schedule

The mission redesign resulted in a SIM-PlanetQuest development schedule that led to a launch readiness date (LRD) of March 2011. Given NASA's recent redirection towards implementation of the Vision for Space Exploration (VSE)[6], the 2007 President's Budget assumes a 2015 LRD for SIM, resulting in a delay of about four years. This delay is due entirely to funding constraints resulting from this shift in NASA priorities, resulting in insufficient funds being available to move the project forward, even though it is technically ready to do so.

9.3 Operations Schedule

Post-launch, there is a sixty-day on-orbit checkout to verify correct system operation, followed by a 120-day science verification period during which the instrument is calibrated prior to turn over to routine operations. The required science mission is 5-years but substantially improved science results accrue from achieving the goal 10-year mission. Regardless of mission duration, the end of on-orbit operations is followed by 20-months of final data reduction and archiving.

9.4 Implementing Organization

Figure-14 shows the current SIM-PlanetQuest development team and their roles. The Jet Propulsion Laboratory (JPL) is the lead

Figure 14: SIM Team

center for the mission and instrument development. Northrop Grumman Space Technology (NGST) will develop the spacecraft, instrument precision structure subsystem (PSS) and will lead the Assembly, Test and Launch-Operations (ATLO) of the flight system as well as providing in-flight spacecraft operations. The Michelson Science Center (MSC) on the campus of the California Institute of Technology (CIT) will host the SIM-PlanetQuest Science Operations System (SOS). The Kennedy Space Center (KSC) will acquire the launch vehicle and conduct launch operations through orbit insertion.

9.5 Current Status & Prognosis

The SIM-PlanetQuest mission is currently in Phase B working toward its mission preliminary design review (PDR) with full support from the user science community. Technology development is complete and the development team is in place ready to proceed towards full-scale development. SIM-PlanetQuest's launch readiness date will be primarily determined by the funding profile that NASA can support given its current priorities relative to the Vision for Space Exploration, in which SIM-PlanetQuest plays a part. The SIM-PlanetQuest team is currently fully ready to proceed to launch.

10. SUMMARY

The SIM-PlanetQuest mission is a key element in the Navigator Program within the Search for Origins NASA theme. SIM-PlanetQuest is the only mission in NASA's future mission suite 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-PlanetQuest also supports a broad astrophysics program that will enhance our knowledge of our Milky Way and other galaxies as well as establishing a new stellar reference frame and significantly improving our calibration of the distance scales for measuring the universe.

SIM-PlanetQuest has completed the technology development required to demonstrate readiness to proceed to full-scale development and has the team in place to accomplish this development. Plans are in place that could support a launch date as early as 2011 but the actual launch readiness date will be determined by the funding profile that NASA is able to support, currently targeted at 2015, as it proceeds towards implementation of the Vision for Space Exploration.

ACKNOWLEDGMENTS

The contents of this paper represent the combined efforts of the hundreds of scientists, engineers and support personnel from the Navigator Program[9] and SIM-PlanetQuest project teams, whose superb efforts have generated the technology results and these concepts and designs which hold so much promise of future scientific discovery.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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SIM-PlanetQuest: Progress Report

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ABSTRACT

SIM-PlanetQuest is a NASA astrophysics mission that is implementing the National Research Counsel's recommended Astrometric Interferometry Mission (AIM) to develop the first, in-space, optical, long-baseline Michelson Stellar Interferometer for performing micro-arcsecond-level astrometry. This level of astrometric precision will enable characterization of planetary systems around nearby stars and enable a number of key investigations in astrophysics including calibration of the cosmological distance scale, stellar and galactic structure and evolution, and dark matter/energy distribution. This paper provides an update on the SIM-PlanetQuest Mission covering the results of the 2005 mission redesign and the recent completion of the last in a series of technology "gates". The SIM-PlanetQuest mission redesign was directed by NASA to recover eroded mass and power margins and to meet specific implementation cost targets. The resulting mission redesign met all redesign objectives with minimal impact to mission science performance. This paper provides the mission redesign objectives and describes the resulting mission and system design including changes in science capability. SIM-PlanetQuest also completed the last of eight major technology development gates that were established in 2001 by NASA, completing the enabling technology development. The technology development program, the last gate, and its significance to the project's flight verification and validation (V&V) approach are briefly described (covered in more detail in a separate paper at this conference). An update on project programmatic status and plans is also provided.

Keywords: Interferometer, Interferometry, astrometry, SIM, PlanetQuest, exo-planets, planet-finding

1. INTRODUCTION

The SIM PlanetQuest mission (formerly known as the Space Interferometry Mission, and hereafter referred to simply as SIM, resulted from the 1991 recommendation of the U.S. National Research Council's (NRC) Astronomy and Astrophysics Survey Committee (AASC)[1] that the U.S. National Aeronautics and Space Administration (NASA) undertake an Astrometric Interferometry Mission (AIM) that would employ the then recently developed, and still evolving, techniques for ground-based, optical, long-baseline interferometers in a space mission that would extend the performance into the few micro-arcsecond (μas) regime by eliminating the effects of Earth's atmospheric disturbance. The NRC envisioned a broad array of scientific objectives, including a broad astrophysics program and characterization of extra-solar planetary systems, and the demonstration of technologies needed to enable future very large space-based telescopes by breaking the linkage between resolving power and aperture size.

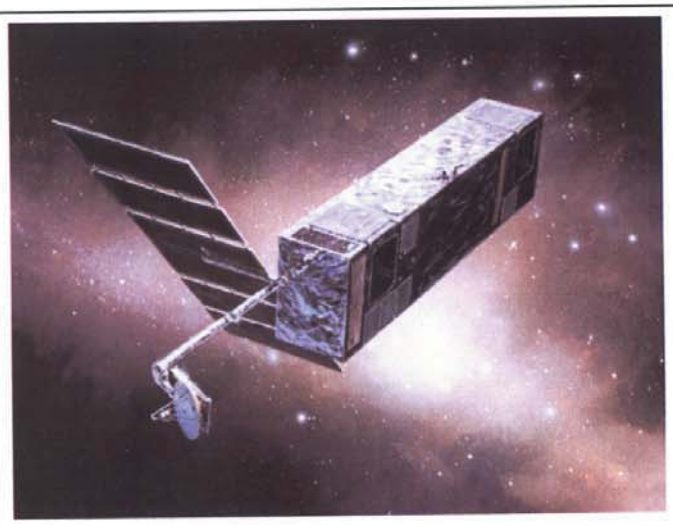

Figure 1: SIM-PlanetQuest Flight System

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The NRC's AIM mission was renamed the SIM in late 1996 following a NASA selection from competing design concepts and project management was assigned to the Jet Propulsion Laboratory (JPL) in Pasadena, California. SIM was later renamed SIM-PlanetQuest in 2005 to emphasize SIM's role in exo-solar planetary system characterization. The NRC's AASC again endorsed the mission in its 2001 Decadal report[2], refining the objectives slightly and shifting additional focus to the characterization of extra-solar planetary systems due to the increasingly frequent discovery of large planets using ground-based radial-velocity, photometric, and other techniques. SIM's scientific capabilities cited were: *"...[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."* The report also emphasized the dual capability of SIM, noting that this capability would enable *"...both narrow-angle astrometry for detecting planets and wide-angle astrometry for mapping the structure of the Milky Way and other nearby galaxies."*

The NRC AASC's Panel on Ultraviolet, Optical and Infrared Astronomy (UVIOR Panel)[3] stressed that "the primary scientific objective of the SIM mission is ultrahigh-accuracy astrometry." SIM's capabilities for making distance measurements of "*1 percent accuracy to distances of several kiloparsecs and of 10 percent accuracy throughout the Galaxy*" would address the astrophysical goals of "*providing a firm foundation for the understanding of stellar astrophysics ... [making] luminosity determinations for key classes of stars ... [to] reduce the calibration uncertainties in the cosmological distance scale ... [and refining] our knowledge of the distribution of dark matter.*" The UVOIR Panel stated that *"[s]earching for planets near stars in the solar neighborhood is the most ambitious of SIM's goals ... [because the search] should generate a preliminary survey of the local planetary population and a more extensive survey of the Jovian-mass planets ... and ... [thereby] not leave any ambiguity about the masses of extrasolar planets."*

The search for extra solar planets was further endorsed in 2004 as a key element of the U.S. President's Vision for Space Exploration (VSE)[6] which included the objective: "*Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars*".

In January 2005, the project was directed by NASA to undertake a mission redesign to address eroding mass margin (relative to the launch vehicle capability) and increased estimated mission cost. The project was requested to provide at least two possible design options to meet two different development cost targets and was allowed that all top level requirements would be open to revision in order to meet the cost targets. In July 2005, the project presented NASA with the mission redesign results, presenting two options, one meeting each of the two cost targets given to the project that differed from one another primarily in the size of the collecting aperture (one at 75% of pre-redesign collecting area and one at 50% of pre-redesign collecting area). Following the mission redesign presentation to NASA, the project was directed to continue the development of the larger collecting area option. With the exception of slightly longer integration times resulting from the smaller collecting aperture, there was little other overall impact to mission science capability, with predicted capability remaining very close to the mission capability goals.

2. ASTROMETRIC MEASUREMENT CAPABILITY

SIM measures the position and proper motions of stars in one of two observing modes: Narrow Angle (NA) or Wide Angle (WA).

The NA mode is probably the easiest to understand in that in this mode SIM measures the position of a target star relative to nearby reference stars (four or more) that are within about 1° of the target star by 'chopping' between them to measure their relative positions over time. The NA mode is the more accurate of the two modes enabling accuracy to about 1 μas.

Science Observation	Target Magnitude	Minimum Performance	Baseline/Full Performance	Goal* Performance
Nearby Stars	7 mag	3 μas	3 μas	1.09 μas
Grid Stars	10.6 mag	10 μas	10 μas	3.35 μas
Legacy NA	10 mag	3 μas	3 μas	1.37 μas
Legacy WA	18 mag	30 μas	10 μas	4.89 μas
Faint NA	13 mag	N/A	N/A	2.87 μas
Faint WA	19 mag	N/A	N/A	35.0 μas

* Goal performance is protected by 30% margins in the design point allocations.

Table-1: SIM-PlanetQuest Performance

NA observations are made by sequentially alternating (chopping) between a target star and a number of nearby surrounding reference stars located within about 1-degree of the target star. This chopping removes instrument drifts, enabling the most accurate performance from the SIM

instrument. A single set of target/reference-star measurements (on the order of 10 chops between the target and the set of reference stars) is called a single NA observation and represents a stand-alone measurement. Accuracy achieved will depend upon star brightness (see Table 1).

The WA mode measures the position of stars ultimately relative to a set of distant quasars. This is done by collecting the positions of target stars measured relative to each other within each of about 1,300 overlapping 15° tiles that cover the entire sky, with each tile being visited repeatedly over the full 5-year mission. The positions of all of the stars and some instrument parameters are then solved for all at once, producing stellar positions accurate to between 4 μas and 30 μas, depending upon the star brightness and the length of integration time on that object. A subset of the observed WA stars called Grid Stars are of magnitude 10.6 or brighter mostly K-giants whose positions will be determined to an accuracy of better than 4 μas and will serve as a full-sky optical reference grid that will be tied to the International Celestial Reference Frame (ICRF).

WA observations are made over the instrument's entire fifteen-degree field-of-regard (FOR) and consist of a single measurement of each star's position. Since measurements of stars within the FOR (about 50 of them) occur over about a 1-hour period, there are larger errors in WA measurements than for NA measurements.

SIM-PlanetQuest's astrometric measurement accuracy specified at three levels: Minimum (the worst it can be before reconsideration of the mission occurs), Baseline/Full (the required performance from NASA's perspective), Goal (the desired capability of the system, from which the SIM project's current design point is derived). NA and WA Minimum and Baseline performance are independent of stellar brightness but goal performance is not. Table-1 shows these SIM-PlanetQuest performance objectives for various target star brightnesses. The Legacy NA and Legacy WA numbers compare to pre-redesign Goals of 1.0 uas and 4.0 uas, respectively, with the new values resulting from a slightly shorter post-redesign instrument baseline (9 m vs prior 10 m).

3. SCIENCE: PLANET FINDING

The NASA's Science and Mission Directorate (SMD) has been developing a number of missions that will contribute to characterization of proto-planetary discs, planetary systems and planets themselves. None of these missions tell the whole story by themselves. Each mission provides pieces of the puzzle that will enable assembling solid understanding of how planetary systems form, their distribution, their characteristics and whether any harbor Earth-like planets (considered to be rocky planets in the range 0.5 to 10 Earth masses) in their habitable zones (where liquid water can exist, considered to be 0.75 to 1.5 AU but scaled with star brightness, see Catanzarite, el al[8]), that are about the same density as our rocky planets so that they have a solid surface (giving diameters of about 0.5 to 2 times the diameter of the Earth), that are far enough away from their parent star to avoid tidal lock, and that actually exhibit characteristics that we would recognize as indicating the presence of biological activity. Additionally, we would like to know that there are gas giants in these same systems much further away (ala Jupiter) that can sweep out comets sufficiently to allow life to evolve on the Earth-like planet(s) in these systems.

The Kepler[7] 4-year mission, currently slated for launch in 2008, will characterize the frequency of occurrence of rocky planets in inner orbits around about 100,000 14th magnitude or brighter dwarf stars lying in a 12 degree field of view pointed in the direction of the Cygnus constellation. Kepler uses the transit method whereby the light intensity from a star dips during the transit of a planet (requiring, of course, that the planetary system by oriented in such a way that the planets cross the line of site between the star and Kepler, estimated to be ~0.5% to ~1%). Most of the stars that Kepler will observe are very distant (out to about 3000 light years, ly) compared to the stars that SIM will characterize (out to ~100 ly). If such planets are very common, Kepler should find something like a few hundred rocky planets.

What Kepler primarily does is to answer the currently unknown fundamental question as to the relative frequency of occurrence of rocky planets around dwarf stars (like our Sun). Kepler's results will be used to tailor SIM's planet observing program. Should Kepler show that rocky planets be rare, SIM will use its planetary discovery time to survey a greater number of nearby stars (~250) for larger rocky planets in habitable zones. Should rocky planets be common, SIM will survey fewer stars (in the range 60 to 120) but will search deeper for smaller planets. SIM will survey the best candidates for planetary systems within 30 pc and will be able to detect planets of all sizes around all of those surveyed, returning orbital parameters and mass [see Catanzarite, et al].

In addition for looking for close-by inner orbit rocky planets, SIM will characterize the planetary architecture of some 2,000 stars by looking for planets in the range from Uranus (14 Earth masses) to Jupiters (318 Earth masses).
Unlike Kepler, SIM will be able to detect planets around every star that has them, regardless of the orientation of the planetary disk. Also unlike Kepler, SIM will determine the mass of any planets discovered and, in fact, is the only NASA mission capable of determining planetary mass, the most fundamental property of a planet and one that is key to the existence and characteristics of the planet's atmosphere. Also unlike Kepler, all planets discovered by SIM will be close enough that they will be candidates for direct planet observation by missions such as the Terrestrial Planet Finders (TPFs)[4] (TPF-C for reflection spectrum and TPF-I for emission spectrum) or later Terrestrial Planet Imagers (TPIs).

SIM planet finding science programs will consume about one-third of SIM's total Science observing time. Of the planet-finding program time, about half has already been allocated to the three Key Projects already selected. Details of all of the investigations already selected can be found on the SIM-PlanetQuest website [Ref TBD]. The remaining time will be allocated through competitive proposal calls about the time that SIM enters full scale development (Phase C/D, in the NASA lifecycle).

4. SCIENCE: ASTROPHYSICS PROGRAM

The remaining approximately two-thirds of SIM science mission time is used for astrophysics objectives that can be accomplished with SIM's precision astrometric capabilities, the primary reason for the original NRC recommendation that NASA undertake the precision astrometry mission that has become SIM. While astrometry is one of the oldest of sciences, the precision offered from a space advantage opens vast new horizons for science based upon accurate measurements of stellar size, mass, distance and motion. SIM's science program aims to take advantage of SIM's micro-arcsecond class measurements to open these vistas using both of SIM's observing modes (WA and NA).

About half of SIM's astrophysics science observing time has been allocated to a set of seven astrophysics Key-Projects and the observing programs of five Mission Scientists, all of whom were competitively selected by NASA. The details of each of these programs can be found on the SIM-PlanetQuest website[10] that has both summaries of their programs and their full proposals. These programs were selected early in the development of SIM to enable the teams to accomplish preparatory science that includes radial velocity pre-screening of candidate objects and to perform fundamental research that will enable teams to better plan their observing and data reduction programs.

The projects of the current science team will contribute to areas such as: How did the galaxy form and how is it evolving now?; What are the masses and mass distributions of nearby galaxies?; What is the nature of dark galactic matter?; How old are the oldest stars in the galaxy?; What are the masses of the stars?; What is the rotation of our local apparent standard of rest?; How do optical and radio images register at the smallest angular scale?; What is the origin, structure, and evolution of the 'central engines' in the nuclei of quasars and active galaxies (AGNs)?.

Future solicitations will address three additional categories of projects that have been identified to date: General Observer (GO), Legacy and Archival Research. General Observer (GO) programs are for smaller projects that do not require significant preparatory science and are usually for one or two years in duration. Legacy programs are programs that will have lasting scientific value. Archival Research proposals are proposals that will utilize archived data (after a proprietary period has expired) to address other scientific questions that may be mined from that data.

Outside of the science observation time allocations, the project will also undertake WA observations of stars from a set of approximately 1300 (mostly K-giant at distances of ~1kpc) Grid Stars distributed roughly uniformly over the entire sky that will be used to develop a quasar-anchored reference grid of stars whose positions are known to an accuracy of better than 10 μas (goal 3.4 μas). These will be related to the International Celestial Reference Frame (ICRF), a primarily radio frequency frame, for use by future astrophysics missions.

All science observing time (planets and astrophysics alike) for the second 5-years of mission life (Goal mission), should that be obtained, will be open for competitive selection.

Further information about SIM's research opportunities is available on the SIM-PlanetQuest web site[10].

5. INTERFEROMETER TUTORIAL

Interferometers are a form of sparse aperture telescope and can combine light from multiple telescopes in either an image plane (Fiseau), forming an image, or in a pupil plane (Michelson), forming (for point sources like stars) a white light interference fringe. SIM-PlanetQuest is a Michelson interferometer operating in the visible portion of the spectrum (400 to 1000 nm). The advantage of a pupil plane interferometer over a filled-aperture telescope is higher resolution but this is at the expense of field of view and fewer photons collected per unit time (which isn't a problem if looking at relatively bright objects).

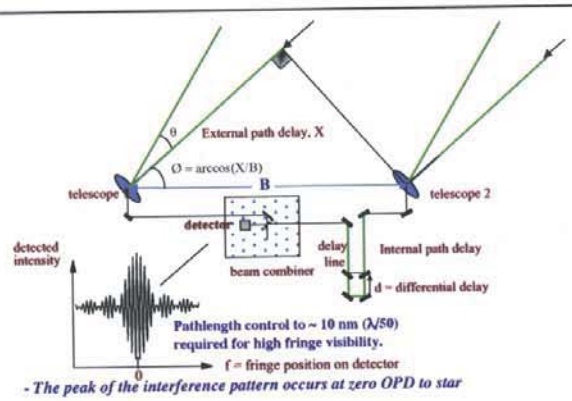

Figure 2: A Single Interferometer "Sensor"

Figure 2 shows a single interferometer "sensor", consisting of two collector telescopes separated by a baseline, B, a delay line and a beam combiner. Light from a star (*not* located at right angles to the baseline, B) arrives at the further collector telescope slightly later than its arrival time at the nearer collector telescope resulting in an external (or geometric) optical path delay (OPD). Optics route the light from the two collector telescopes back to the beam combiner, inserting in the nearer telescope leg an internal optical delay equal to the external delay in the other leg, resulting in the optical path lengths being matched to within a few nanometers. Internal laser metrology is used to measure the inserted internal optical delay as an analog for the external geometric optical delay.

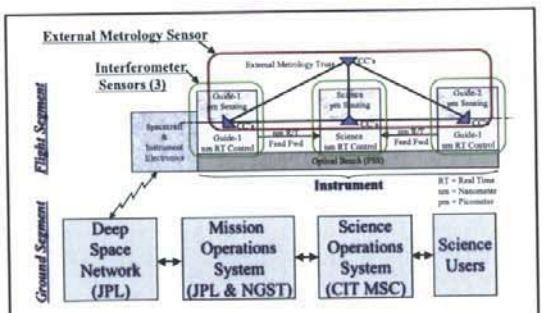

Figure 3: SIM Building Blocks

Assuming that one can determine the length and orientation of the interferometer baseline, B, then one can solve for the angle of the incoming stellar wavefront. Much of SIM-PlanetQuest's complexity revolves around determining these parameters. In practice on SIM-PlanetQuest, angles are measured between closely spaced stars by alternating (chopping) between these stars relatively quickly in order to remove system drifts.

6. SYSTEM CONFIGURATION

Figure 3 shows the building blocks of the SIM-PlanetQuest system. The flight segment consists of one large facility-class instrument, a 3-axis stabilized spacecraft, a launch vehicle and a launch vehicle adapter. The ground segment consists of the Deep Space Network, a Mission Operations System and a Science Operations System (the launch vehicle ground control system is considered part of the launch vehicle).

6.1 Instrument

The SIM-PlanetQuest instrument consists of three visible-wavelength Michelson (pupil plane) stellar interferometer sensors (each like Figure 2) and one external metrology sensor, all supported by a Precision Structure subsystem (PSS) and controlled by the Real-Time Control (RTC) subsystem. Instrument layout is shown in Figure-4.

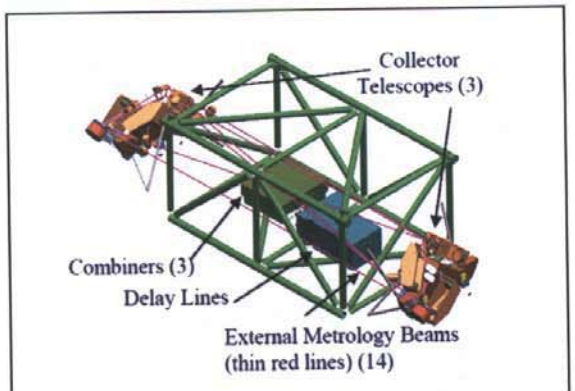

Figure 4: SIM Instrument Layout

One of the three Michelson stellar interferometers has a baseline of 9 meters and serves as the Science interferometer. The other

two interferometers have a somewhat shorter baseline (7.2 m) and serve as Guide interferometers (essentially forming a micro-arcsecond two-axis star tracker) to stabilize the line of sight of the Science interferometer. The Guides track relative bright stars at opposite edges of the field of regard (FOR), generating stabilizing feed forward control information for the science interferometer (to enable making science measurements on dim stars down to visual magnitude 19 in brightness) as well as feeding precision attitude information to the spacecraft attitude control system to reduce the size of the ACS dead-band and thus reduce beam-walk on the instrument optics.

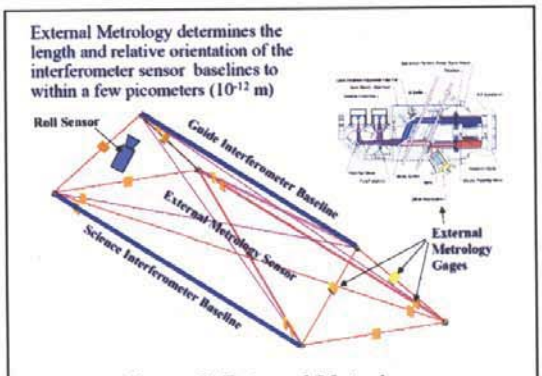

Figure 5: External Metrology

The External Metrology sensor shown in Figures-4 &-5 is a laser truss that measures the baseline length and relative orientation of the three interferometers. The truss consists of fourteen laser beams launched by fourteen metrology gauges that are each capable of measuring the distance between optical corner cube fiducials to an accuracy of a few picometers. This truss is used in non-real-time to reconstruct on the ground where the optical elements were located relative to each other as a function of time, correlated to science measurements.

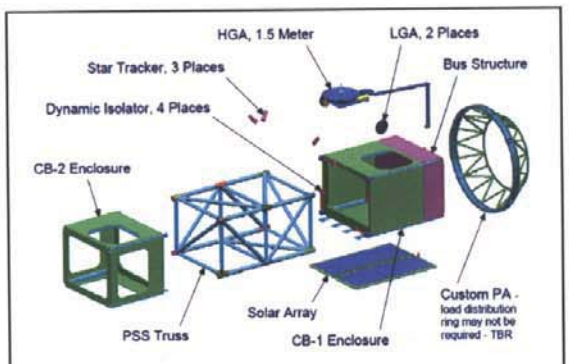

Figure 6: Structural Layout

The Precision Structure subsystem (PSS) is a composite truss structure that supports the components of the interferometer and the collector bay enclosures as shown in Figures-4 and -6. Instrument optical elements (collector telescopes, delay lines and combiners) are connected to the PSS via support struts. Thermal radiators are mounted on the top surface of the PSS that is always facing away from the sun (the top surface of the PSS is a sun exclusion zone). Thermal control for the PSS is provided by the Spacecraft. Vibration isolation between the spacecraft and the PSS is provided by four passive viso-elastic dynamic vibration isolators shown in Figure-6.

The Real Time Control (RTC) subsystem is physically mounted in the Spacecraft bus structure and contains three RAD 750 flight computers, and associated electronics to control the entire instrument. Intra-instrument communications is handled via a modified SpaceWire (IEEE 1393) ring bus.

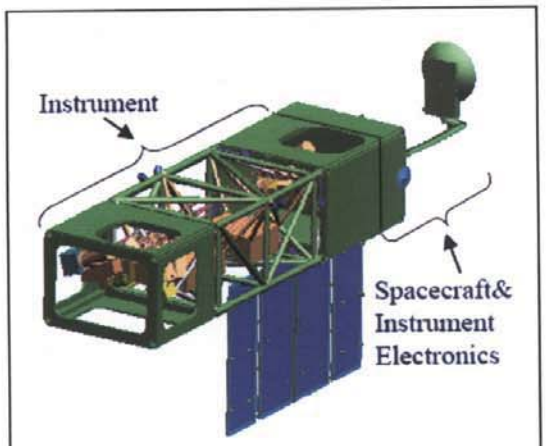

Figure 7: Deployed Flight Segment

6.2 Spacecraft

The SIM-PlanetQuest spacecraft is a generic spacecraft suitable for a deep space mission and is mounted to one of the collector bay enclosures inside of a bus structure (Figure-6) that also encloses a portion of the instrument electronics. The spacecraft provides a KA-band telecom system, 6-kw GaAs solar array, 512 Gbit solid state recorder, six vibration-isolated reaction wheels, a monoprop momentum unloading system, thermal control and provides the mounting point for the launch vehicle adaptor.

6.3 Flight Segment Configuration

The full spacecraft-instrument configuration is shown fully deployed in figure-7.

6.4 Launch Vehicle

SIM-PlanetQuest will launch on either an Atlas V 551 or a Delta IV Heavy launch vehicle from the Kennedy space center, Cape Canaveral, Florida, USA. Figure-8 shows the flight segment packaged for launch in a 5m x 19m "long" faring suitable for either of these two vehicles. Selection of the particular vehicle will be made at the start of full-scale development.

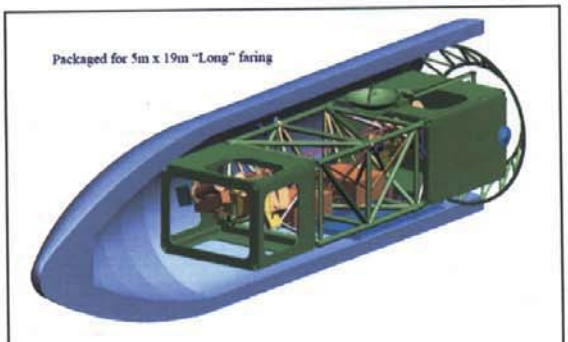

Figure 8: Packaged for Launch

6.5 Mission Operations System

SIM-PlanetQuest will utilize the NASA Deep Space Network (DSN) and Advanced Multi-Mission Operations System (AMMOS) services as the base for the project mission operations system. The SIM-PlanetQuest spacecraft will be operated by Northrop Grumman Space Technologies (NGST) from their Redondo Beach, CA, facility and the Instrument will be operated from the Jet Propulsion Laboratory (JPL) in Pasadena, CA.

6.6 Science Operations System

Science operations will be coordinated by the SIM-PlanetQuest Science Operations System (SOS) located at the Michelson Science Center (MSC) on the campus of the California Institute of Technology (CIT) in Pasadena, CA, USA. The SOS will provide the primary interface to the science user community and will provide uplink observation planning and downlink science data processing and distribution functions. Additionally, the SOS will coordinate science user proposal calls and selections.

6.7 Integration Sequence

Figure-9 shows the assembly sequence for the flight segment. The instrument system subsystems are assembled at the Jet Propulsion Laboratory (JPL) in Pasadena, California, USA, where functional testing in air will be completed. The instrument will then be shipped to Northrop Grumman Space Technology (NGST) in Redondo Beach, CA, USA, where it will be performance tested in vacuum. The spacecraft will also be separately functionally and performance tested at NGST prior to mate with the instrument for final testing prior to ship to Cape Canaveral, Florida, USA for launch operations.

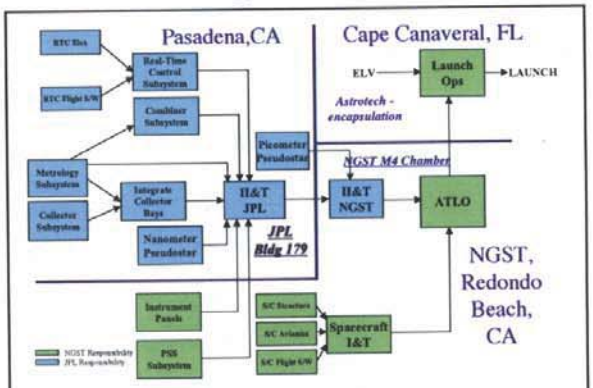

Figure 9: Integration Flow

7. TECHNOLOGY COMPLETION

The SIM-PlanetQuest technology development program has been underway for the better part of a decade. Eight technology Gates (Figure-10), taken from the full SIM technology development plan, were established in 2001 by NASA 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) of six (out of nine levels) has been reached, signifying readiness to proceed to flight hardware development.

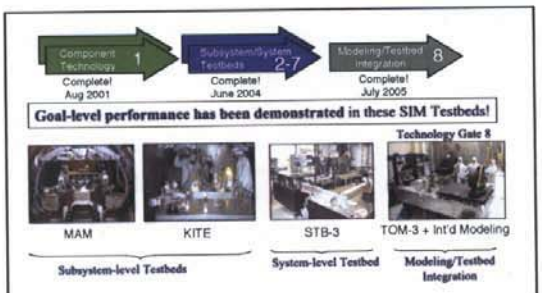

Figure 10: Technology Completion

These eight Technology Gates spanned the range from component technologies to system level technologies that demonstrate not only system performance in relevant environments but also demonstrates the methodology that will be used to test and demonstrate performance of the flight system.

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

The last of these Technology Gates was key in that it demonstrated the integration of specific test data into an overall model of the instrument and mission to predict overall mission performance, demonstrating the methodology to be followed during the full flight system integration and test. Work in support of this technology gate also demonstrated that the instrument 'sensors' (the three single interferometer sensors or the external metrology sensor) can be performance tested separately (i.e., they do not interfere with each other) and the results combined via models, verifying the viability of this approach for flight instrument performance verification.

Completion of the full SIM technology development program was formally signed-off by NASA in March 2003 following extensive review of all technology program objectives and their status by three external review teams.

8. SCIENCE OPERATIONS

SIM-PlanetQuest will be launched into an Earth-Trailing Heliocentric Orbit (ETHO) that takes the system away from the time varying thermal influence of the Earth. The orbit selected is slightly more elliptical than Earth's orbit resulting in a gradually increasing distance (~0.1 AU/year), looping apparent distance

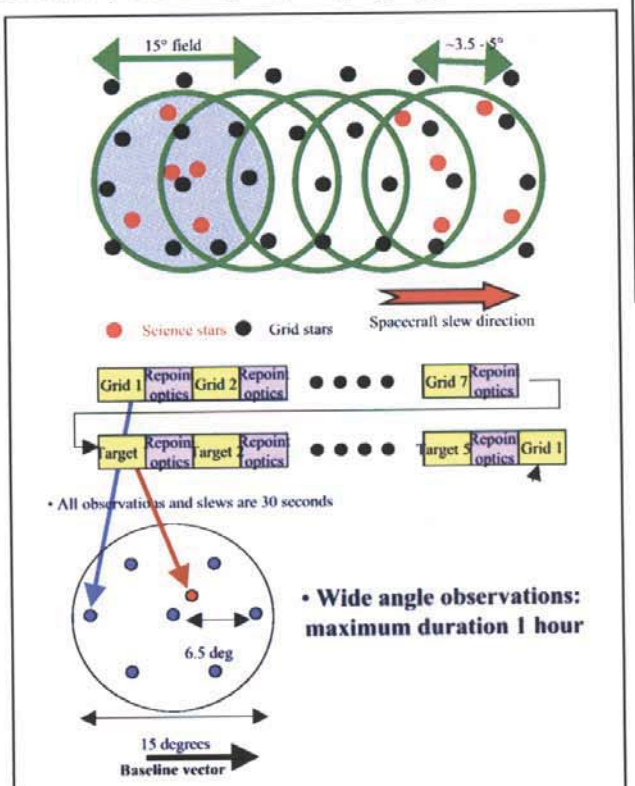

Figure 12: Wide Angle Observing Scenario

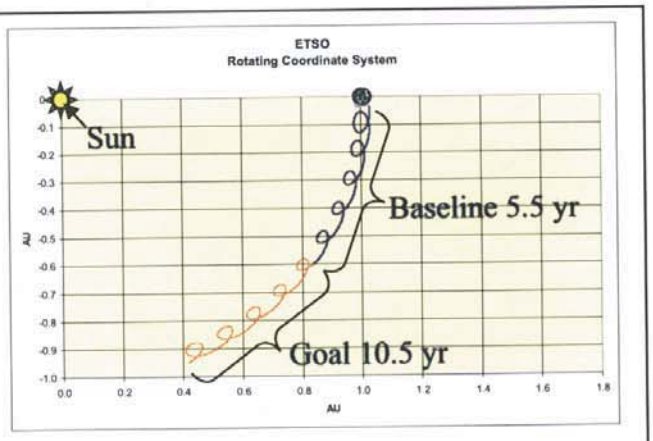

Figure 13: SIM-PlanetQuest Drift-Away ETHO

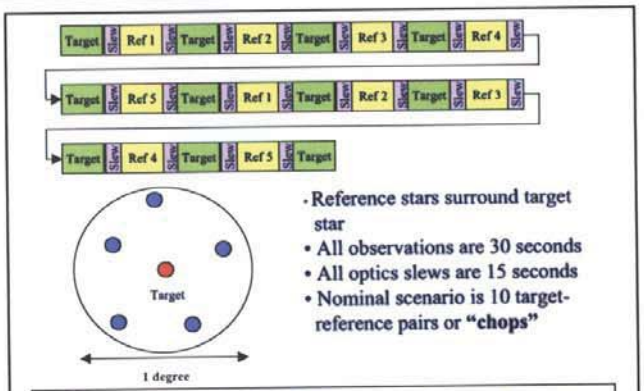

Figure 11: Narrow Angle Observing Scenario

between SIM and the Earth (Figure 11). This increasing distance from Earth with mission time results in increasing coverage requirements from the NASA Deep Space Network (DSN) as the mission progresses, being driven during the early mission by velocity determination requirements but later by the demands of maintaining telecom downlink volumes as the Earth-spacecraft distance increases during the mission.

SIM-PlanetQuest observes the sky in 15° 'field of regard' (FOR) 'tiles' (about 1,300 of them) that are obtained by positioning the spacecraft orientation until the two Guide interferometers have acquired their guide stars and then using the science interferometer's siderostat (moveable telescope mirror) to observe targets anywhere in the full 15° FOR. During each tile, various types of targets might be observed, including Grid stars, WA targets and NA targets. A typical tile takes about an hour. Subsequent tiles overlap previous tiles by roughly half so that one or more identical Grid stars can be observed for each tile orientation, providing the means to tie the tiles together. Over a relatively short time, each target within a tile needs to be observed with the instrument in roughly orthogonal orientations in order to obtain a two dimensional position for the object. Observing scenarios for both WA and NA targets are shown in Figures 12 and 13.

9. PROJECT STATUS

9.1 Mission Redesign

In January 2005, NASA directed the project to redesign the mission to meet specific cost targets and to restore margins that had become eroded due to changing launch vehicles from the ill-fated Columbia space shuttle to an expendable launch vehicle. This mission redesign was completed in July 2005 with a report to the NASA Science and Mission Directorate (SMD), meeting all requirements of the mission redesign with little overall impact to project science and with a design that did not require any new technology development.

Changes that were made during the mission redesign included: reduction in the science interferometer baseline length from 10m to 9m; reduction in the size of the science interferometer telescope to 75% of its pre-redesign collecting area; and elimination of the spare science interferometer which had been carried for redundancy, resulting in meeting redundancy requirements at lower levels of the design. These changes had the net effect of reducing the predicted design point performance slightly (WA from 4 μas to 4.9 μas; NA from 1 μas to 1.4 μas). For Grid stars (using stars brighter than 10.6th magnitude) and Planet-finding (using stars brighter than 7th magnitude) the overall performance essentially unchanged from pre redesign performance. The revised performance is still factors of several better than that requested by the NRC in their two decadal reports (see the introduction).

9.2 Development Schedule

The mission redesign resulted in a SIM-PlanetQuest development schedule that led to a launch readiness date (LRD) of March 2011. Given NASA's recent redirection towards implementation of the Vision for Space Exploration (VSE)[6], the 2007 President's Budget assumes a 2015 LRD for SIM, resulting in a delay of about four years. This delay is due entirely to funding constraints resulting from this shift in NASA priorities, resulting in insufficient funds being available to move the project forward, even though it is technically ready to do so.

9.3 Operations Schedule

Post-launch, there is a sixty-day on-orbit checkout to verify correct system operation, followed by a 120-day science verification period during which the instrument is calibrated prior to turn over to routine operations. The required science mission is 5-years but substantially improved science results accrue from achieving the goal 10-year mission. Regardless of mission duration, the end of on-orbit operations is followed by 20-months of final data reduction and archiving.

9.4 Implementing Organization

Figure-14 shows the current SIM-PlanetQuest development team and their roles. The Jet Propulsion Laboratory (JPL) is the lead

Figure 14: SIM Team

center for the mission and instrument development. Northrop Grumman Space Technology (NGST) will develop the spacecraft, instrument precision structure subsystem (PSS) and will lead the Assembly, Test and Launch-Operations (ATLO) of the flight system as well as providing in-flight spacecraft operations. The Michelson Science Center (MSC) on the campus of the California Institute of Technology (CIT) will host the SIM-PlanetQuest Science Operations System (SOS). The Kennedy Space Center (KSC) will acquire the launch vehicle and conduct launch operations through orbit insertion.

9.5 Current Status & Prognosis

The SIM-PlanetQuest mission is currently in Phase B working toward its mission preliminary design review (PDR) with full support from the user science community. Technology development is complete and the development team is in place ready to proceed towards full-scale development. SIM-PlanetQuest's launch readiness date will be primarily determined by the funding profile that NASA can support given its current priorities relative to the Vision for Space Exploration, in which SIM-PlanetQuest plays a part. The SIM-PlanetQuest team is currently fully ready to proceed to launch.

10. SUMMARY

The SIM-PlanetQuest mission is a key element in the Navigator Program within the Search for Origins NASA theme. SIM-PlanetQuest is the only mission in NASA's future mission suite 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-PlanetQuest also supports a broad astrophysics program that will enhance our knowledge of our Milky Way and other galaxies as well as establishing a new stellar reference frame and significantly improving our calibration of the distance scales for measuring the universe.

SIM-PlanetQuest has completed the technology development required to demonstrate readiness to proceed to full-scale development and has the team in place to accomplish this development. Plans are in place that could support a launch date as early as 2011 but the actual launch readiness date will be determined by the funding profile that NASA is able to support, currently targeted at 2015, as it proceeds towards implementation of the Vision for Space Exploration.

ACKNOWLEDGMENTS

The contents of this paper represent the combined efforts of the hundreds of scientists, engineers and support personnel from the Navigator Program[9] and SIM-PlanetQuest project teams, whose superb efforts have generated the technology results and these concepts and designs which hold so much promise of future scientific discovery.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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