IAC-05-A3.1.04

SIM-PLANETQUEST MISSION: OVERVIEW AND CURRENT STATUS

James C. Marr-IV
SIM-PlanetQuest Deputy Project Manager
NASA Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California, U.S.A.
James.C.Marr@jpl.nasa.gov

ABSTRACT

The SIM-PlanetQuest Mission will be the first, in-space, optical, long-baseline Michelson Stellar Interferometer. SIM-PlanetQuest will perform precision astrometry at the micro-arcsecond accuracy level, which will be used to characterize planetary systems around stars within ten parsecs of the Sun and address a number of other key issues in astrophysics including calibration of the cosmological distance scale and mapping of galactic structure. This paper provides a broad overview of the SIM-PlanetQuest Mission, covering: history, science objectives, key top level requirements, how the mission will be implemented (technical and programmatic), technology development status, an assessment of where the project is today, and prognosis for the future. SIM-PlanetQuest supports the U.S. President's Vision for Space Exploration and is supported by the U.S. National Academy of Sciences.

BACKGROUND

The U.S. National Research Council's (NRC) Astronomy and Astrophysics Survey Committee (AASC), in its 1990 decadal report[1], recommended 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 interferometers but applied from a vantage point outside of Earth's constantly varying atmospheric turbulence to enable extending astrometric precision into the few micro-arcsecond (μas) regime. The NRC envisioned a broad array of scientific objectives including astrophysics and characterization of extra-solar planetary systems. The science goals were specified as[5]: "*... definitive searches for planets around stars as far away as 500 light-years through the wobbles of the parent star, trigonometric determination of distances throughout the galaxy, and the study of the mass distributions of nearby galaxies from stellar orbits.*" An additional objective for SIM was to develop technologies needed to enable future very large space-based telescopes by breaking the linkage between resolving power and aperture size.

The NRC's AIM mission was renamed the Space Interferometry Mission (SIM) in late 1996, following a NASA selection from competing design concepts, and management was assigned to the Jet Propulsion Laboratory (JPL) in Pasadena, California, U.S.A.. SIM was later renamed SIM-PlanetQuest in 2005

to emphasize SIM's role in exo-solar planetary system characterization as a part of the parent Navigator Program (see below). JPL continued development of the mission design concept (based on a long-baseline Michelson stellar interferometer) for the rest of the 1990s, refining the science requirements, maturing the necessary technologies that would be needed to achieve the intended unprecedented accuracy and preparing to carry the concept into space. Industrial partners were selected and the first portion of the project science team was competitively selected (by NASA).

The NRC's AASC again endorsed the mission in its 2000 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 around nearby stars using ground based radial-velocity, photometric, or other techniques. Scientific capabilities cited were[5]: "... *[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 the new SIM, noting that this capability would enable[5] "... *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 from Space (UVOIR Panel)[3], stressed that "the primary scientific objective of the SIM mission is ultrahigh-accuracy astrometry." SIM's capabilities for making distance measurements of[5] "*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[5] 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*".

NAVIGATOR PROGRAM: *EXPLORING NEW WORLDS*

The NASA's Science and Mission Directorate (SMD) implemented the Navigator Program (NP), under its Astronomical Search for Origins (ASO) theme[4] within the Universe Division of the Science Mission Directorate (SMD), to characterize planetary systems around stars in our corner of the Milky Way galaxy.

The NP, as currently conceived, will employ a logical sequence of missions to characterize proto-planetary discs, planetary systems and planets themselves that can be found within a few hundred light years of our Sun. Figure-1 shows the NASA sequence of space-based planet-finding-related missions (noting that Kepler and JWST are not formally part of the NP and excluding the NP Keck Interferometer and Large Binocular Telescope ground-based projects). Information regarding all of these missions, including their science goals, can be found on the NASA Navigator Program PlanetQuest web site[7].

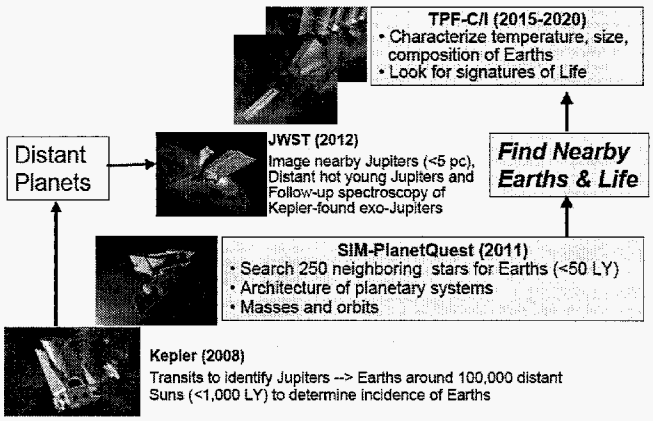

Figure-1: Space Planet Finding Missions

Together this set of missions will provide a clear inventory of planetary systems and answer the age-old question of whether there are other Earth-like planets in habitable zones around nearby stars in our galaxy.

Most of these missions also do significant science other than planet-related science but it is the planet-related part of each mission's science program that serves as the unifying theme within the NP.

SIM-PLANETQUEST MISSION OVERVIEW

SIM-PlanetQuest will be launched from the NASA Kennedy Space Center aboard either an Atlas V 551 or Delta IV Heavy launch vehicle, directly into an Earth Trailing Solar Orbit (ETSO), similar to the orbit used for the Spitzer Space Telescope now in its operational phase. The ETSO results in a slow drift away from Earth at about one-tenth Astronomical Unit (AU) per year, placing increasing demands on downlink telecom as the mission progresses. Following launch and a 60-day on-orbit checkout period, a 120-day science verification period will confirm that the SIM Instrument is functioning and properly calibrated on the sky.

SIM-PlanetQuest is required to complete a 5-year on-orbit mission of routine science operations and has a goal to complete a 10-year mission (see the Science Program section of this paper). During these science operations, SIM-PlanetQuest will sequentially scan the entire sky in 15-degree field-of-regard (FOR) overlapping "tiles", taking astrometric measurements on roughly 50 stars in each tile over about a one-hour time period before moving to the next tile. Currently, different tiling approaches are being studied to determine the tiling sequence that returns the best overall mission accuracy. After science operations are complete, there will be a 20-month period for final data reduction and archival.

SCIENCE PROGRAM

Science Modes: S I M -PlanetQuest observes in two primary observational modes: Narrow Angle (NA) and Wide Angle (WA).

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 the Capabilities section below).

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.

WA observations also include stars from a set of approximately 1100 (mostly K-giant) Grid Stars distributed over the entire sky and 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 3.3 μas).

Capabilities (accuracies under various conditions): SIM-PlanetQuest's astrometric measurement accuracy requirement is specified at three levels: Minimum (the worst it can be before reconsideration of the mission occurs), Baseline (the required performance), Goal (the desired capability of the system but not a requirement). 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.

Mission Time Allocation: Approximately 50% of expected SIM-PlanetQuest science observing time for the first 5-years of mission science observing time has been allocated via competitively selected investigators so far, about half for planet searching and half for astrophysics. This observing time was allocated to 10 Key Projects and 5 Mission Scientists for projects that require significant pre-launch preparatory science. Information about each of these investigations can be found on the SIM-PlanetQuest web site[8].

Science Observation	Target Magnitude	Minimum Performance	Baseline Performance	Goal* Performance
Nearby Stars	7 mag	3 μas	3 μas	1.02 μas
Grid Stars	10.6 mag	10 μas	10 μas	3.28 μas
Legacy NA	10 mag	3 μas	3 μas	1.26 μas
Legacy WA	18 mag	30 μas	10 μas	4.0 μas
Faint NA	13 mag	N/A	N/A	2.5 μas
Faint WA	19 mag	N/A	N/A	29 μas

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

Table-1: SIM-PlanetQuest Performance

Planned Future Science Program: The remaining ~50% of science observing time will be allocated to a number of additional projects, some to be awarded pre-launch and some post-launch. Several categories of projects have been

identified to date. These are: General Observer (GO), Legacy, and Archival Research.

General Observer (GO) programs are for smaller programs 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.

All science observing time 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[7].

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).

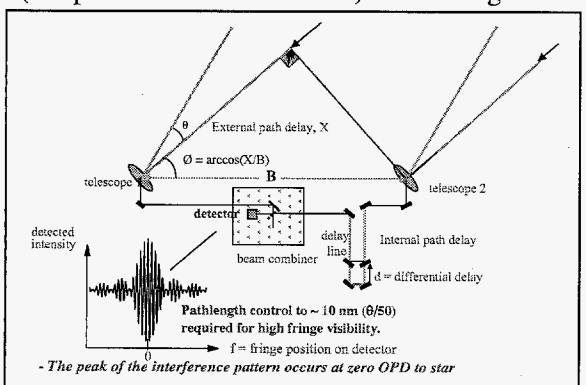

Figure-2: A Single Interferometer "Sensor"

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. 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.

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.

SYSTEM CONFIGURATION

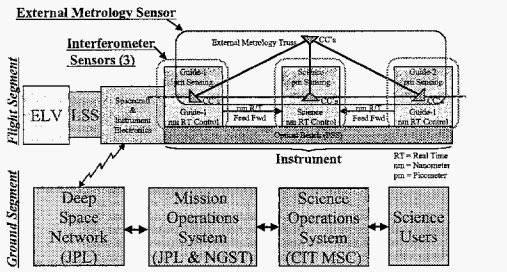

Figure-3: SIM Building Blocks

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).

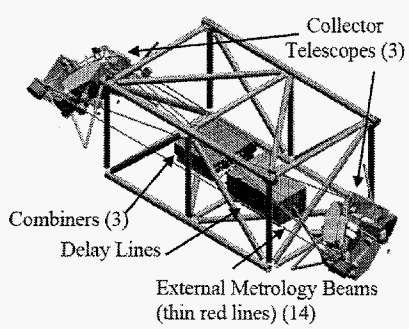

Figure-4: SIM Instrument Layout

Instrument: The SIM-PlanetQuest instrument consists of three visible-wavelength Michelson (pupil plane) stellar interferometer sensors 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.

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.

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.

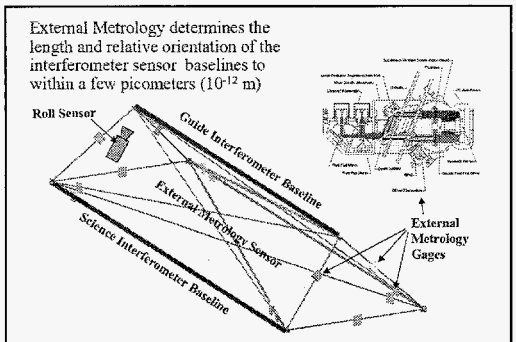

Figure-5: External Metrology

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.

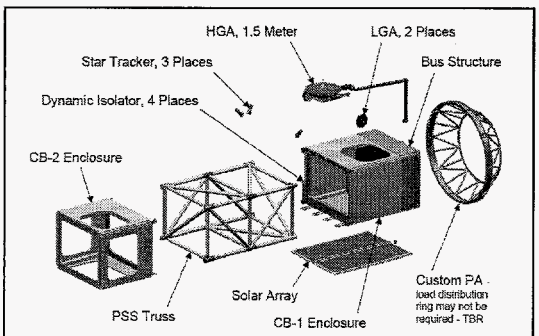

Figure-6: Structural Layout

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 IEEE 1393 ring bus.

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 part 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

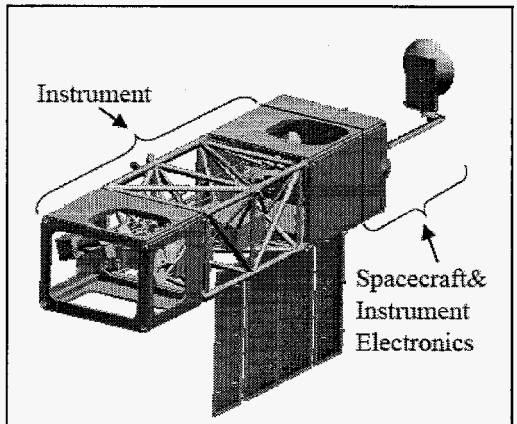

Figure-7: Deployed Flight Segment

reaction wheels, a monoprop momentum unloading system, thermal control and provides the mounting point for the launch support structure (LSS) aka the launch load distribution adapter.

Flight Segment Configuration: The full spacecraft-instrument configuration is shown fully deployed in figure-7.

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.

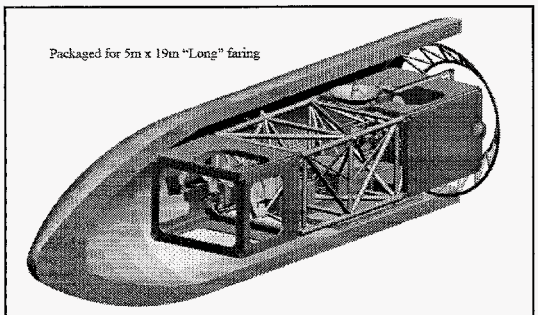

Figure-8: Packaged for Launch

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, USA facility and the Instrument will be operated from the Jet Propulsion Laboratory (JPL) in Pasadena, CA, USA.

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.

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.

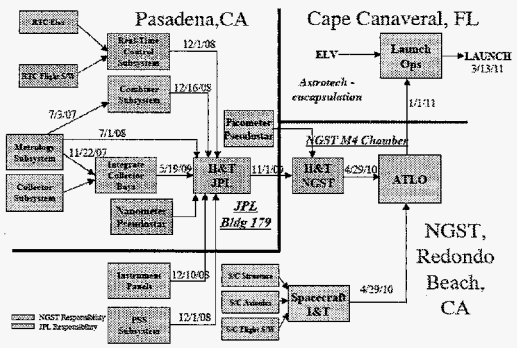

Figure-9: Integration Flow

TECHNOLOGY DEVELOPMENT

The SIM-PlanetQuest technology development program has been underway for the better part of a decade. Eight technology Gates (Figure-10) 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

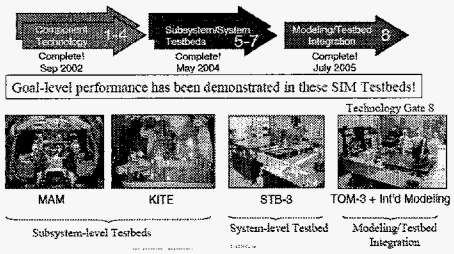

Figure-10: Technology Completion

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 make the commitment for flight hardware development.

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.

PROJECT STATUS

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 Program Management Council, 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.

Development Schedule: Figure-11 shows the current SIM-PlanetQuest development schedule that leads to a

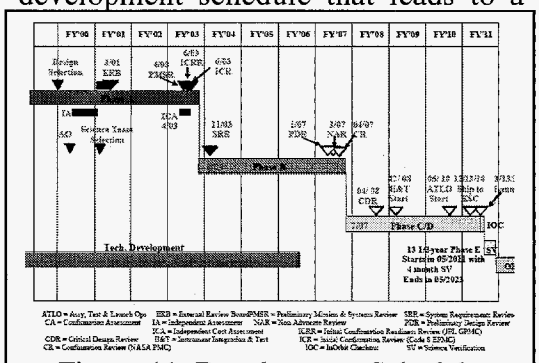

Figure-11: Development Schedule

launch readiness date (LRD) of March 2011. Given NASA's recent redirection towards implementation of the Vision for Space Exploration (VSE)[6], it is not yet clear that the funding profile required to support this LRD will be available.

Operations Schedule: Figure-12 shows the operational phase 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

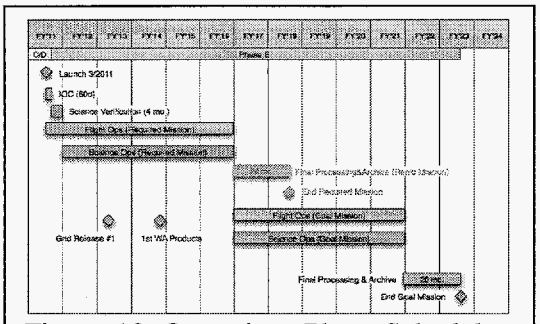

Figure-12: Operations Phase Schedule

duration, the end of on-orbit operations is followed by 20-months of final data reduction and archiving.

Implementing Organization: Figure-13 shows the current SIM-PlanetQuest development team and their roles. The

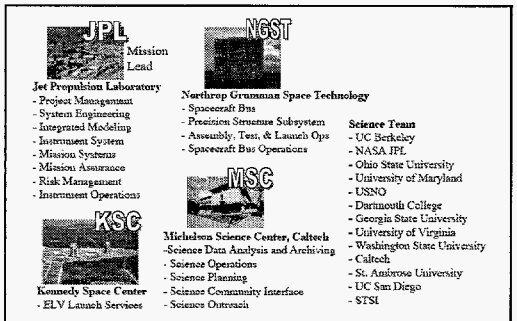

Figure-13: SIM Team

~~NASA~~ Jet Propulsion Laboratory (JPL) is the lead 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.

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 essentially 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, of which SIM-PlanetQuest is a part.

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 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 will support an earliest feasible launch date of March 2011 but the actual launch readiness date will be determined by the funding profile

that NASA is able to support 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 and SIM-PlanetQuest project teams, whose superb efforts have generated these concepts and designs which hold so much promise of future scientific discovery.

at The research described in this paper was carried out ~~by~~ the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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.

REFERENCES

1. Astronomy and Astrophysics Survey Committee, National Research Council. 1990. *The Decade of Discovery in Astronomy and Astrophysics* (Washington, D.C.: National Academy Press)
2. Astronomy and Astrophysics Survey Committee, National Research Council. 2000. *Astronomy and Astrophysics in the New Millennium* (Washington, D.C.: National Academy Press)
3. Astronomy and Astrophysics Survey Committee, National Research Council. 2000. *Astronomy and Astrophysics in the New Millennium Panel Reports: Panel on Ultraviolet, Optical, and Infrared Astronomy from Space (UVOIR)* (Washington, D.C.: National Academy Press)
4. Origins Science Subcommittee, Space Science Advisory Committee to NASA, Origins 2003 – Roadmap for the Office of Space Science Origins Theme, NASA JPL: http://origins.jpl.nasa.gov/library/roadmap03/index.html ?
5. J.H. McElroy & J.P. Huchra, co-chairs of the National Research Council (NRC) Committee on Astronomy and Astrophysics (CAA), letter to Dr. Ed Weiler, NASA Associate Administrator for Space Science, 9/12/05 in response to his (Weiler's) request for a CAA review of SIM.
6. *A Renewed Spirit of Discovery, the President's Vision for U.S. Space Exploration*, The White House, January 2004
7. Navigator Program PlanetQuest web site: http://planetquest.jpl.nasa.gov/index.cfm. check
8. SIM-PlanetQuest web site: (http://planetquest/SIM/sim_index.html). check