Navigator Program: Exploring New Worlds

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Abstract— NASA's Navigator Program is a series of interrelated missions to explore and characterize new worlds. Each successive mission provides an essential step toward the ultimate goal of discovering habitable planets and life around nearby stars.

Are there other solar systems like our own? Are there other habitable worlds? Is there life elsewhere in the universe? These questions are timeless, but only in this generation has technology progressed to the state where we can conceive of and build a suite of missions that capable of answering them. The Navigator Program and its missions are described in this paper.

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1. INTRODUCTION

The Navigator Program is structured around the goal of finding evidence of life on nearby planets, out to about 20 parsecs (60 light years) away from our sun. This distance is roughly the distance that technology in the next decade will allows us to probe the atmospheres of other worlds. Extrasolar planets appear in the sky as extremely faint objects located in extreme close proximity to their host stars. The technological challenge is essentially one of high-dynamic range sensing coupled with and high angular-resolution imaging.

Optical/infrared interferometry is a key technology being developed through the Navigator Program. Traditional telescope designs have an achievable resolution that is limited by the diameter of the telescope's primary mirror. When telescopes are combined in an array, the achievable resolution is limited instead by the separation of the telescopes; so that in principle arrays can be built that would have the resolution of single telescopes several hundred meters across. When implemented in space, free from the distortions of the turbulent atmosphere, such interferometers hold the promise of resolving individual planets orbiting nearby stars.

Mirror technology, wavefront control, and coronagraphy are other key approaches being used in the Navigator Program in the search for other worlds. High-dynamic range imaging depends on the achievement of near-perfect wavefronts such that speckles and aberrations created by the reflected starlight don't obscure the presence of faint planets.

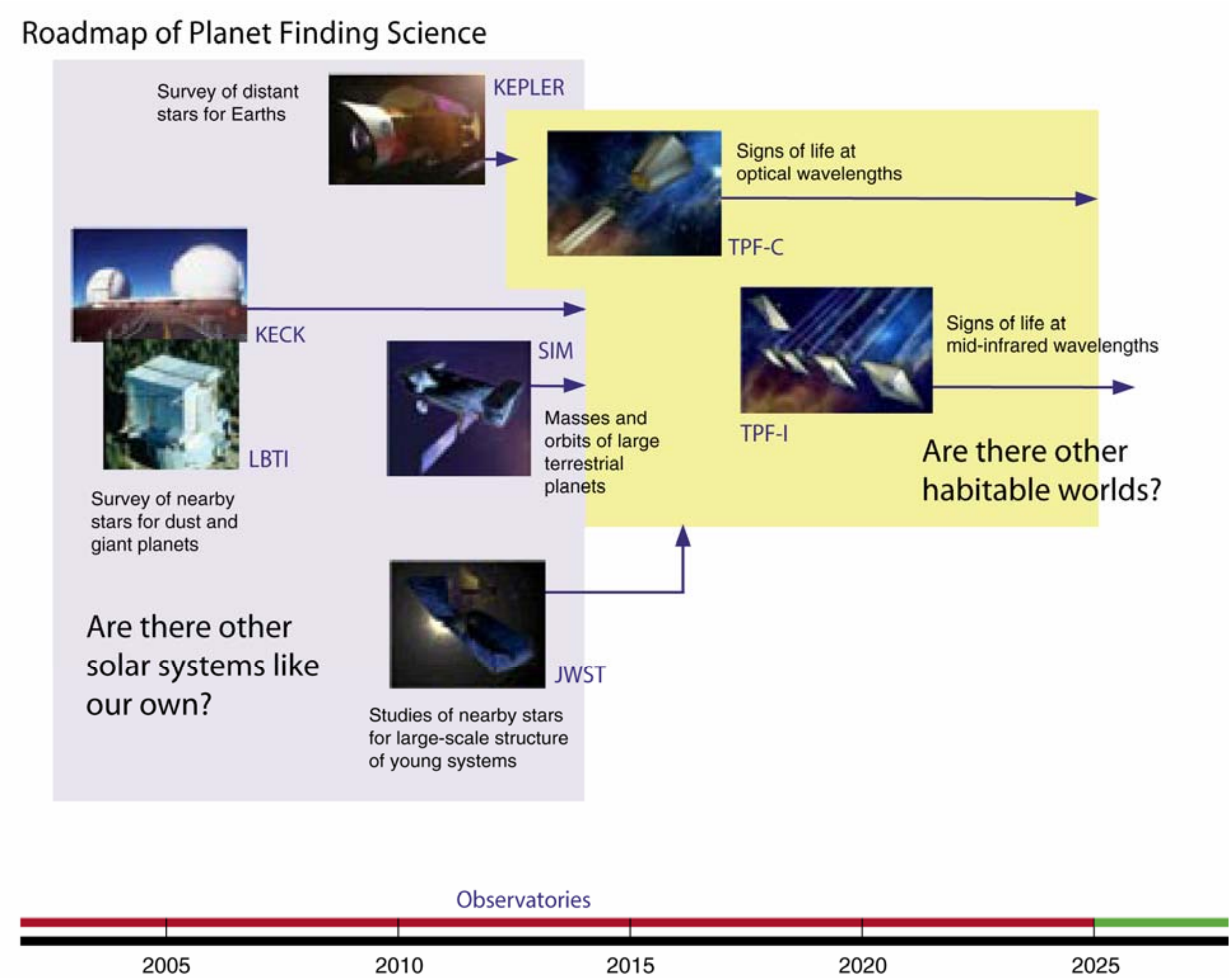
The Navigator Program is being developed at a time when new planets are being found every month, and the pace of planet detection is accelerating. A thorough understanding of new scientific discoveries is of utmost importance to the optimum design of the missions in the program. For example, although it is estimated that Jupiter-mass planets exist around roughly 15 percent of main-sequence stars, the frequency of Earth-like planets is at present unknown – since Earth-mass planets have not yet been detected. Precursor missions and ongoing ground-based science will provide detailed statistics of other planetary systems that will help mature the technology requirements and mission designs. NASA's fostering of the science of extrasolar planets, as well as its engagement of scientists and students, through NASA Research Opportunities and other funding sources, provides a solid foundation of the Program.

2. THE SEARCH FOR EARTH-LIKE PLANETS

Whether the universe harbors other worlds that support life is a question that has been pondered, yet remained unanswered, for over two thousand years. The Navigator Program is structured around three fundamental questions, described in the following.

Are there Other Solar Systems Like Our Own?

The known extrasolar planets have been found, almost exclusively by radial velocity searches, using large ground-based telescopes. These searches have discovered over 150



planets at distances out to about 300 light years from the Sun. These planets are almost exclusively large gas-giant planets that lie in orbits hostile to the emergence of life. A planetary system like our own would have a protected habitable zone, wherein the conditions would be just right to sustain liquid water and life on a planet's surface. Many of the systems found to date have gas giant planets orbiting in or within the bounds of such a zone, making the coexistence of Earth-like planets unlikely. No planets have been detected so far with masses less than 6 Earth-masses, and only a small number of systems have been found with multiple planets. In the near future however, our understanding of the diversity of extrasolar planets will increase dramatically with results from the Kepler Mission, due for launch in 2007. This mission is designed to detect transiting planets including Earth-mass planets out to roughly 2000 light years. Most of these planets will be so far away as to be well outside our reach of being able to directly measure their atmospheres.

Our own solar system has a halo of dust left over from the time of planet formation. This dust provides a bright background around our Sun if it were viewed from many light years away. A question that remains unanswered is how typical is the dust around our own system, and to what extent would its brightness be a barrier against the detection of planets orbiting within it? The characterization of exozodiacal dust is an important part of our understanding of other planetary systems. The Spitzer Space Telescope currently has a program of observing nearby stars to see how bright their infrared background is, and in so doing to provide a catalog of data of potential target stars for planet search missions. The stars nearby our own Sun will also be studied in detail by the Keck Interferometer (KI) and the Large Binocular Telescope Interferometer (LBT-I) to reveal giant planets and dust in the inner regions of these systems. These two interferometers are complementary because they sensitive to different angular scales on the sky around stars.

Our search for life will extend outward to about 60 light-years from us, and in this space we will first need to understand and characterize the planetary systems that exist there. This is not work that will have been accomplished by any other mission, since the transit detections by Kepler are only for those rare occasions when a planet's orbit passes directly across the line of sight to a star. For that reason, Kepler's success is dependent upon a search through a much larger volume of space. The Navigator Program has as one of its goals, an exhaustive planet search through our immediate neighborhood with SIM PlanetQuest as a precursor to other mission. SIM will be capable of detecting planets as small as several Earth masses, and will be able to measure orbits in exquisite detail. Our ability to predict the stars and planetary systems that might support life will be greatly advanced with the results of this mission.

Are There Other Habitable Worlds?

A habitable world is one that has an environment that could support life. The most reasonable home for life elsewhere in the universe is a terrestrial planet, a roughly Earth-sized world, sheltered in the habitable zone of a star. To determine whether a planet is habitable, we must have observatories capable of characterizing the composition of a planet's atmosphere. The Terrestrial Planet Finder Coronagraph (TPF-C) at optical wavelengths, and the Terrestrial Planet Finder Interferometer (TPF-I) at mid-infrared wavelengths, will look for oxygen, water vapor, methane, and carbon dioxide. In the correct ratios, and observed over a broad wavelength range, these gases mark the existence of an atmosphere such as our own out of equilibrium. Through numerous measurements at different epochs, they will be capable of providing unambiguous detections of Earth-like planets and evidence of the habitability of other worlds.

Is There Life Elsewhere in the Universe?

Detecting the presence of a life-supporting atmosphere at the resolution available to TPF-C and TPF-I may not provide conclusive proof of the existence of *life* on other worlds. However, should TPF-C and TPF-I be successful, yet larger observatories will likely follow their lead, having an enhanced sensitivity, and thereby enabling higher-resolution spectroscopy. A comprehensive catalog of atmospheric constituents may then be obtained, and even time-varying spectra of atmospheric conditions measured across several seasons of planetary change.

3. ENABLING TECHNOLOGY

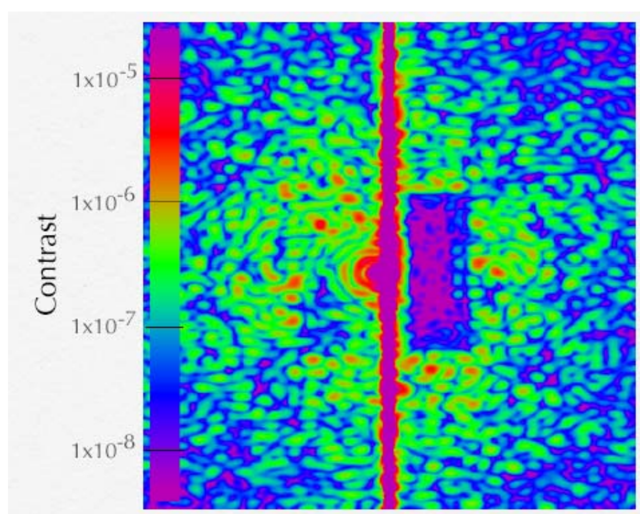
The study of Earth-like planets around other stars will require significant advances in several key technologies. Broadly speaking, these challenges lie in the areas of high-angular resolution sensing and high dynamic range imaging.

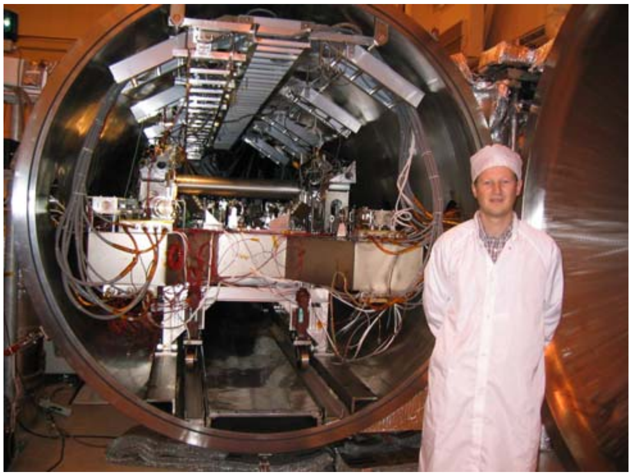
Technology for High Angular Resolution

For an optical space telescope to distinguish the presence of planets around nearby stars, it would need a primary mirror more than 8 or 10-m in diameter. At infrared wavelengths, the telescope would need to be more than 10 times larger, but is nonetheless possible through interferometry – the combination of light from several widely-separated space telescopes. Technology advances in several areas will make these observations possible: 1) Large precision deployable mirrors in space; 2) Laser metrology and systems to sense and control optics and large mechanical structures (30 feet to 300 feet) to within nanometer precision; 3) Wave-front sensing and control to fine-tune the optical surfaces in the telescope at the sub-nanometer level; and 4) Formation flying technology to provide the ultimate in high-angular resolution – the coordination of arrays of free-flying telescopes in space.

Technology for High Dynamic Range Imaging

Extrasolar planets are extremely faint compared to the stars around which they orbit: about a million times fainter at mid-infrared wavelengths and 10 billion times fainter at optical wavelengths. Technology advances in several areas are needed to enable the high dynamic range imaging needed to detect faint planets: 1) Mirror polishing technology to suppress scattered light; 2) Coronagraph and interferometer starlight suppression; 3) Thermal control and cryogenic technology to provide the thermal shielding and the darkest background in which to detect planets; 4) Detector and cooler technology to enable the devices capable of sensing the very faintest extrasolar planets.





4. Mission Descriptions

The science and technology of the different Navigator missions are summarized in the following paragraphs.

Keck Interferometer

The Keck Interferometer (KI) has as its primary goal the characterization of exozodiacal dust around nearby stars, which can hide the infrared signature of orbiting planets, and the characterization of circumstellar disks from which planets form.

KI combines light from the twin 10-meter Keck telescopes. By using the light-collecting area of the world's largest optical telescope, KI greatly increases the sensitivity available with optical interferometry. The subsystems of the interferometer include adaptive optics, laser metrology to control optical delay lines, and fringe tracking to measure the interference in the combined light from the two telescopes. KI achieved first-fringes in 2001, and in August 2005 yielded an interferometric null of 1 part in 100, a milestone in the development of planet-finding technology.

Large Binocular Telescope Interferometer

The Large Binocular Telescope Interferometer (LBTI) will examine and describe the dust and planets around nearby solar systems, as well as provide images of Jupiter-like planets in orbit around these stars. The LBTI uses two 8-meter class telescopes mounted on a single alt-azimuth mount. Because of its unique geometry and relatively direct optical path, the LBTI will offer science capabilities that are different from other interferometers in the Navigator Program. It will provide high-resolution images of many faint objects over a wide field-of-view.

The LBTI is currently under development at the University of Arizona. Science operations are scheduled to begin in 2007.

SIM PlanetQuest

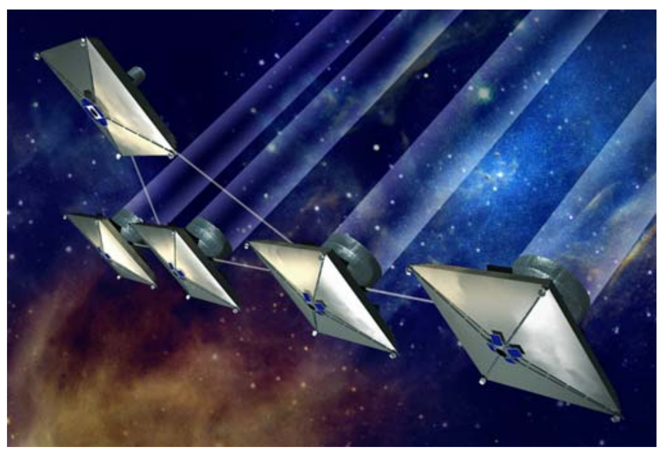
SIM PlanetQuest is a pathfinder in the development of space-based interferometry. The mission combines the light from two 25-centimeter telescopes separated by 9 meters. It will use precise measurements of fringe position to determine orbits of roughly Earth-sized planets around about 150 stars. It will also perform a broader survey of over 2000 stars to look for planets the size of Neptune and larger.

The technology developed for SIM will see direct applications in many of the Navigator missions that follow. As of August 2005, all of its eight technology milestones have been accomplished. Its Preliminary Design Review is scheduled for late 2006. Brassboard hardware of key technology will be completed and tested prior to the review.

Terrestrial Planet Finder Coronagraph

TPF-C will search nearby Sun-like stars for Earth-like planets capable of supporting life. It will look for atmospheric signatures of water, oxygen, and other chemical indicators of life. The mission will

TPF-C is envisaged as a large space telescope operating at visible wavelengths, with an elliptical primary mirror 8 by 3.5 meters in diameter. It will have the most precise optics of any telescope ever built. It will be deployed beyond the Moon's orbit for a mission life of five years, possibly extended to 10 years. TPF-C is now in Pre-Phase A of its development.



Terrestrial Planet Finder Interferometer

TPF-I has the same broad scientific goals of TPF-C and will be designed to be capable of measuring the atmospheres of nearby extrasolar planets. It is being envisaged as an infrared interferometer, using free-flying space telescopes. At wavelengths of 7-17 microns, the resolution required telescope operating at

TPF-I would include five formation flying spacecraft: four 4-meter class mid-infrared telescopes and one combiner spacecraft to which the light from the four telescopes is relayed to be combined and detected. As with TPF-C, TPF-I would be deployed in an L2 orbit, beyond the Moon. TPF-I is also in Pre-Phase A of its development.

Michelson Science Center

The Michelson Science Center (MSC) is a science operations and analysis center that supports numerous Navigator Program missions. It supports science software development, science operations, and the engagement of the science community. The MSC coordinates the Michelson Fellowship Program and Michelson Summer Workshop series.

The MSC is based at the California Institute of Technology and builds on experience gained from the Infrared Processing and Analysis Center and the Spitzer Science Center. The MSC currently supports the Palomar Testbed Interferometer, the Keck Interferometer, SIM PlanetQuest, NASA Keck single-telescope operations, LBTI, and the Michelson Program (mentioned above).

5. Research Opportunities

Support for Navigator precursor science activities is fostered through NASA Research Announcements (NRAs) and coordinated programs managed at the Jet Propulsion Laboratory on behalf of NASA Headquarters. All of these activities contribute to growing the community of scientists engaged in Navigator-related research. Young researchers, in the early stages of their career, are provided support through the Michelson Fellowship Program to engage in new science and technology programs related to Navigator. A much broader network of scientists is being fostered through coordinated activities with the European Space Agency – most noteworthy among these activities is the TPF/Darwin conference series that annually brings together over 200 scientists from the United States and Europe. Input and guidance from scientific community is also provided at the twice-yearly meetings of the Science Working Groups (SWG) for each Navigator mission. The work of SWG members is typically focused on the development of the science objectives and priorities for the missions, but also includes more direct participation in reviews of progress with TPF-C and TPF-I.

Many of the research activities described as Navigator precursor science naturally fall within the scope of the research announcements within NASA Research Opportunities in Space and Earth Science (ROSES). Most notable amongst these are the opportunities for *Origins of Solar Systems* and *TPF Foundation Science*. The TPF Foundation Science NRA is particularly relevant because it provides a mechanism for peer-review and directed funding emphasizing Navigator science.

6. Engaging Students and the Public

The Navigator Program is actively pursuing a vigorous program of education and public outreach, which includes the following activities:

(1) The Center for Astronomy Education: Empowering faculty to improve learning and retention in college-introductory astronomy programs (with an emphasis on community colleges).

(2) The Night Sky Network: A network of over 200 astronomy clubs holding hundreds of events around the country and sharing the science, technology and inspiration of NASA missions

(3) Hands-on Universe: An educational program that enables students to investigate the universe while applying tools and concepts from science, math, and technology.

(4) Educational Webcasts: Connecting large and diverse audiences to the experience of future space exploration and the ongoing story of the search for another Earth.

(5) PlanetQuest Thematic Website: Bringing the latest planet-finding news, science, and technology to the public.

7. Conclusions

The discovery of another habitable planet will without doubt be one of mankind's most significant achievements in the 21st century. The Navigator Program is working to make this vision a reality.

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Biography

Peter Lawson is a System Engineer at the Jet Propulsion Laboratory. He obtained his Ph.D. at the University of Sydney (Australia)in 1994, and held postdoctoral positions at the Observatoire de la Cote d'Azur and the University of Cambridge. He is Chair of the IAU Working Group on Optical/Infrared Interferometry. He also chaired the Michelson Interferometry Summer Schools from 1999-2002, and has edited two books on stellar interferometry, as well as numerous JPL publications related to the Terrestrial Planet Finder missions.