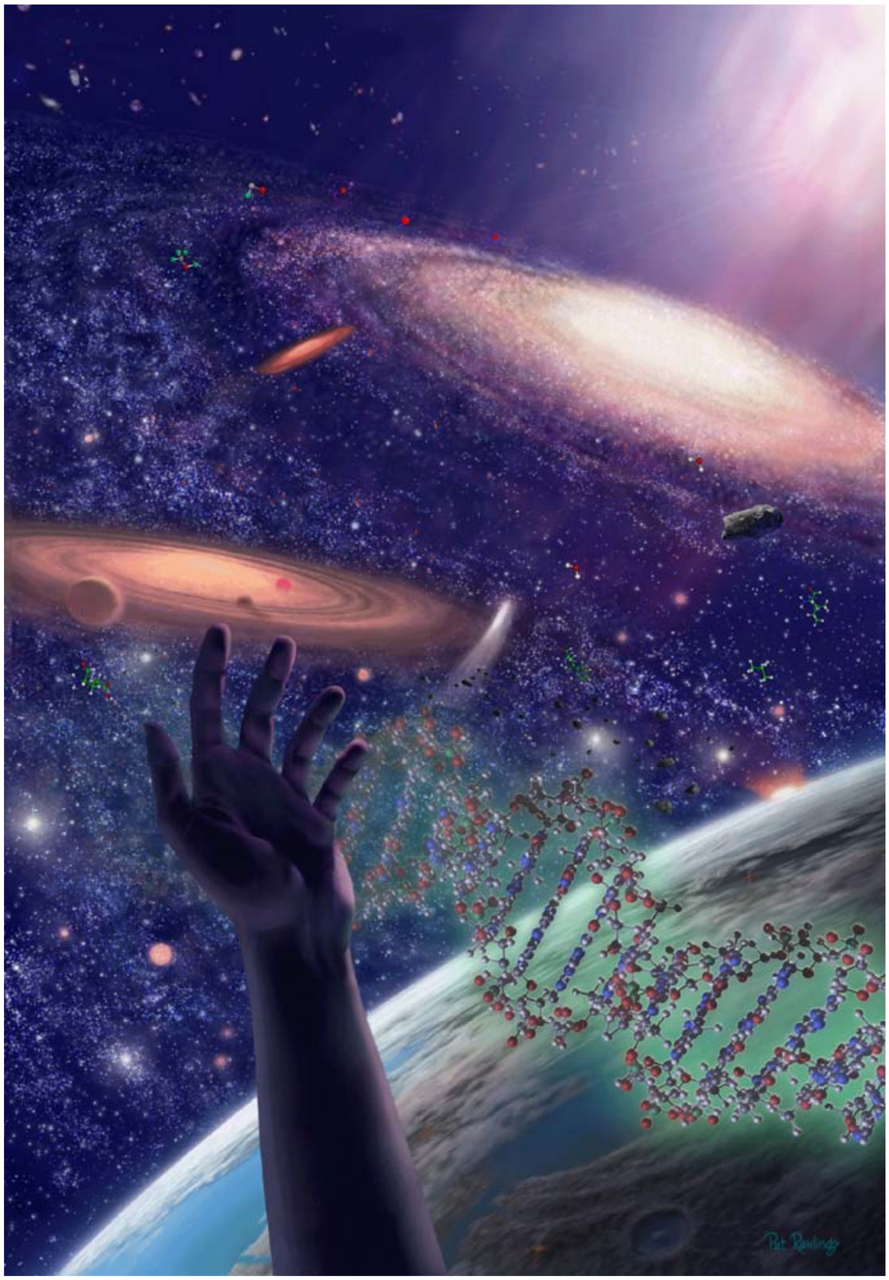
I. Agency Objective Statement, Strategic Roadmap #4:

"To conduct advanced telescope searches for Earth-like planets and habitable environments around neighboring stars."



Strategic Roadmap #4, "**The Search for Earth-like Planets,**" builds on a strong legacy of scientific advances and policy heritage (see Appendix 1) and represents NASA's *only* plan for realizing these exploration goals.

II. Key Science Goals: The Search for Habitable Planets, the Development of Habitable Environments

Are we alone? In the vast blackness of the Universe, our home planet is a single sparkling oasis of life. Whether the Universe harbors other worlds that can support life is a question that has been pondered, yet remained unanswered, for thousands of years. While we continue to search for sub-surface life on other worlds in our Solar System, we are privileged to live in a time when technological advances allow us to expand the search for life beyond the confines of our own Solar System, and out into the wider Universe. Over the next two decades, NASA will launch a series of spaceborne telescopes that will build on a foundation of existing observatories and progressively advance humanity's ability to detect and characterize Earth-like planets around other stars, and examine those planets for signs of life. This program directly supports *The President's Vision for US Space Exploration* (2004) that calls for *"advanced telescope searches for Earth-like planets and habitable environments around other stars"* as one of NASA's exploration goals in the 21st Century.

Within the first 10 years of this Roadmap, we will know whether Earth-like planets are common or rare. We will also know whether any nearby stars have Earth-mass planets, and we will be on the verge of knowing whether any nearby exoplanets show biosignatures indicating the possible presence of life. Missions in later decades will successively reveal the presence, formation, and diversity of Earth-like planets and any life they may harbor.

This Roadmap has two scientific themes that will lead to these and other discoveries. The first theme is the search for extrasolar planets and their direct detection and characterization, and the second is the study of the formation and evolution of exoplanetary systems from stellar disks. This Roadmap will delineate the investigations and the missions that make up these two themes.

A. Do other stars harbor planets like Earth?

The search for extrasolar planetary systems is well underway, and we now know of over 150 planets outside our Solar System, most discovered by NASA-supported ground-based telescopes and with the help of NASA-supported grants.

While some of these planets are gas giants similar to Jupiter and Saturn in our Solar System, some of the newly discovered planets have masses as small as 15 times the mass of the Earth.

These recent discoveries have already revealed important insights:

- Planets are quite common. Roughly 7% of all nearby stars harbor a giant planet within 3 AU.
- The number of planets increases as mass decreases towards the mass of an earth.
- Stars that contain higher abundance of metals are more likely to have planets

- Multiple planets are common, often in resonant orbits
- The number of planets increases with distance from the star.
- Eccentric orbits are common, with only 10% being nearly circular.

The increasing number of planets with smaller mass suggests that planets with masses below 15 Earth masses, currently undetectable, are even more numerous. Moreover, the correlation with heavy elements supports current planet formation theory that suggests rocky planets would be more numerous than the gas giants. *The observations suggest that many nearby stars harbor rocky planets.*

Doppler planet search techniques have found all but 5 of the ~150 known extrasolar planets. Over the next few years, these Doppler planet searches are poised to discover Jupiter-mass planets orbiting at 4-7 AU, providing the first direct comparison of planets in our Solar System to those orbiting at comparable distances from other stars. Jupiter analogs, those in circular orbits having no giant planet inward of them, may be signposts of rocky planets orbiting closer in, thus serving to prioritize target stars for SIM – PlanetQuest, Terrestrial Planet Finder-Coronagraph (TPF-C), and Terrestrial Planet Finder-Interferometer (TPF-I). Doppler work with a precision of 1 m/s would allow detection of planets having mass as low as 10 Earth masses, but most easily if they orbit within 0.1 AU of a solar-mass star, a region that is hotter than the corresponding habitable zone. Earth-mass planets orbiting at roughly 1 AU induce a stellar wobble of only 0.1 m/s, a factor of 10 below the detection threshold of even future Doppler work. Thus, other space-borne techniques are needed to find Earth-like planets, first indirectly with SIM and then directly with TPF-C and TPF-I.

While current observations suggest that rocky planets *may* be common, their abundance is quite uncertain. *Kepler* will address this question statistically by surveying stars 200-600 parsecs away (one parsec is equal to 3.26 light-years). *Kepler* will detect Earth-sized planets (and larger) through their rare alignment with the host star, dimming it by one part in 10,000. Planets found by *Kepler* will be too distant for follow-up by SIM-PlanetQuest or TPF. SIM-PlanetQuest and TPF will survey nearby stars and determine the abundance of nearby Earth-like planets.

B. What are the properties of these planets?

Discovery will be but the first step in our exploration of extrasolar rocky planets. Next, we will want to learn the basic properties of each newly discovered planet. The diversity of rocky worlds is likely much greater than that represented by Mercury, Venus, Earth, and Mars. SIM-PlanetQuest, TPF-C and TPF-I will begin the process of exploring these new planets by measuring their fundamental properties:

- *Mass.* The SIM-PlanetQuest mission will directly measure the masses of the larger rocky planets. The mass of a rocky planet determines whether it can retain molecules in its atmosphere. The presence of greenhouse gases in the atmosphere determines the planet's temperature. Mass also sets the geochemical and thermal structure of the interior of the planet, which dictates the presence of plate tectonics (affecting the cycling of surface material), active volcanism, and magnetic dynamos (that provide magnetic protection from cosmic rays). Mass discriminates ice-giants from rocky planets that otherwise differ little in radius.

- *Surface Temperature and Radius.* The temperature of rocky planets will be measured unambiguously by the combination of TPF-C and TPF-I. The direct images themselves provide orbital distances, which imply temperatures from radiative equilibrium, albeit with an uncertainty due to the unknown albedo (light reflection fraction) and greenhouse effects. By combining measurements of the reflected visible fluxes (setting albedo) made by TPF-C and of the mid-IR fluxes (setting planet luminosity) made by TPF-I, we can uniquely determine the radius and surface temperature of the planets. These measurements by TPF-C and TPF-I will establish the habitability of each detected rocky planet. Table II-1 summarizes the scientific synergies between SIM, TPF-C, and TPF-I.

- *Atmospheric Composition.* TPF-C and TPF-I will acquire low-resolution spectra of rocky planets enabling the first measures of the chemical composition of their atmospheres. The spectroscopic observations will be designed to detect oxygen, ozone, carbon dioxide, and methane in the planet's atmosphere. These spectroscopic observations will also be essential for our search for biomarkers (next section).

- *Surface Properties.* TPF-C/TPF-I will search for temporal variability in the brightness of the rocky planets caused by the rotation of surface features and clouds. TPF-C can get direct spectral measurements of planetary surface composition (rock, ocean, ice, vegetation) and TPF-I will be able to discriminate CO_2 ice-covered worlds with thin atmospheres. By measuring such variations over many rotation periods, these observations will reveal whether the planet has clouds, oceans, and continents. These temporal observations will also reveal the rotation period of the planet and could detect annual global variations in planetary properties. Remote observations of the Earth would reveal significant daily variations in its brightness.

By measuring these basic properties, the planned suite of missions will determine whether any of the nearby planets are suitable environments for detectable life.

Table II-1: Physical Parameters Determined by SIM, TPF-C, and TPF-I. Red plus signs mean that all the missions are required to determine the parameter; black checks mean that the indicated parameter can, in principle, be obtained by the one mission alone.

Parameters	SIM	TPF-C	TPF-I
Orbital Parameters			
– Stable orbit in habitable zone	✓		
Characteristics for habitability			
– Temperature			✓
– Temperature Variability due to distance changes	✓		
– Radius		+	+
– Albedo		+	+
– Mass	✓		
– Surface gravity	+	+	+
– Atmospheric and Surface Composition		✓	✓
– Atmospheric conditions		✓	✓
– Presence of water		✓	✓
– Temporal Variability of composition		✓	✓
Solar System Characteristics			
– Influence of other planets	✓		
– Presence of comets or asteroids		✓	
Indicators of Life			
– Atmospheric Biosignatures (e.g., O_2, O_3, CH_4)		+	+
– Surface Biosignatures (e.g., vegetation red edge)		✓	

Checkbox chart indicating which missions will contribute to determining various physical parameters for extra-solar planets. All missions in the plan are required to fully characterize extra-solar planetary systems.

C. How will we detect the presence of life?

Our search plans assume that the effects on a planet of even the most basic forms of life are global, and that biosignatures from the planet's atmosphere or surface will be recognizable in the disk-averaged spectrum of the planet. Observations and exploration of our own and other planets in our Solar System, and ongoing astrobiology research, have taught us that signs of life can *only* be conclusively recognized in the context of the overall planetary environment.

The Earth has known surface biosignatures from vegetation, and several atmospheric biosignatures, including the characteristic spectra of life-related compounds like oxygen – produced by photosynthetic bacteria and plants - and its photochemical product, ozone. A more robust atmospheric biosignature is the simultaneous presence of oxygen or ozone and a reduced gas, such as methane (CH_4) or nitrous oxide (N_2O), which are also produced by life. Although these latter two gases are difficult to detect in the Earth's current atmosphere they and other biogenic compounds may be more detectable on Earth-like planets around other stars or during different stages of a planet's history.

Life, and the conditions under which life thrives, may not be identical to those found on Earth. Correspondingly, we must design missions that are as robust as possible in thoroughly characterizing planets of unknown composition, and in searching for the byproducts of metabolisms that may not be familiar to us. To do this, we must observe over the largest wavelength range possible, to provide confirmation detections of the same molecular species, and to increase our overall chances of detecting and interpreting biosignatures in the context of their planetary environment. This will maximize the probability of success in our search for extrasolar life and provide crosschecks and verification tests for what could be the most important scientific and cultural discovery of the century. A marginal detection of oxygen in the visible could be verified with a follow-up detection of the stronger ozone in the mid-IR. Having data in two different wavelength regions would also help with the identification of the secondary biomarker gases such as CH_4 and N_2O. CH_4 can be observed in both the visible and the thermal infrared, although detection in the mid-IR can be problematic in the presence of strong absorption from water vapor, whereas N_2O can only be seen in the mid-IR. In addition, many metabolic byproducts of life have absorption features that are accessible only in the mid-IR. On the other hand, surface signatures of life, such as those from leafy plants on Earth, can only be detected in the visible range. Thus, robust detection and quantification of biosignatures from the widest possible range of potential metabolisms would require data in both wavelength regions. Not only does this allow access to a more comprehensive array of potential biosignatures from different types of life, the two wavelength regions also provide the crucial characterization of the planetary environment required to identify the biomarker in context. It is very clear that if we do eventually make a tentative identification of life in one wavelength region, the information that we will need to corroborate it is data from the other wavelength region.

Beyond the TPF missions, the next generation “Life Finder” mission would use a greater collecting area to provide enhanced spectral resolution, better temporal resolution, and improved overall sensitivity. This would enable a more sensitive search for additional biosignatures, and extend our search for Earth-like worlds to perhaps thousands of stars. The dual goals of extending our search to further planetary systems and providing greater resolution, time-resolved, spectral information will challenge our imagination and technical prowess, particularly in the area of large, lightweight space optics, for decades to come.

To support these observational missions, it is very important to explore possible biosignatures in great detail, both theoretically and in the field or laboratory, to better understand those signs of life that might be remotely detected in the spectrum of another planet, especially for habitable planets that differ from our own modern Earth, in age or composition. It is also important to identify potential “false positives,” the non-biological generation of planetary characteristics that mimic biosignatures. The NASA Astrobiology Institute and the TPF-Foundation Science program support research that will help determine the design and characterization strategies for the TPF and successor missions. This research will determine the most robust characterization strategy via the synergistic use of planetary mass from SIM, and the complementary optical and infrared spectral information provided by the TPF and Life Finder missions.

To ultimately understand whether we are part of a living Universe, we can only extrapolate outward. If life is found anywhere within our stellar "neighborhood," then we can conclude it to be highly probable that life is common in our galaxy, and surely so in the wider Universe. Conversely, if present or past life is found to be absent from our stellar neighborhood except for here at home, then this information surely will inform our view of how rare life is anywhere in the Universe, and how precious it is on Earth.

> The Extrasolar Habitable Zone
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> The Habitable Zone classically refers to that range of distances from a star in which an Earth-like planet can maintain liquid water on its surface. The inner edge of the habitable zone is governed by the catastrophic loss of surface water into the atmosphere, and the outer edge is governed by the freezing out of water on the planetary surface.
>
> Our exploration of our own Solar System suggests that the habitable zone may be larger. There is growing evidence that sub-surface environments on Mars and Europa, regions outside of the classically defined Habitable Zone, might be conducive to life. However, life deep under rock or ice would be extremely difficult to detect via remote sensing, even from orbit. Thus, the "Extrasolar Habitable Zone", the region where life could both exist and be remotely detected, is used for planning the astronomical remote-sensing reconnaissance to be undertaken by the TPF missions and LifeFinder.

D. How does star formation lead to planet formation?

The Sun, our home star that provides our planet with warmth and light, was formed from a dense cloud of dust and gas 4.5 billion years ago and will continue to shine at nearly the same brightness for another 5 billion years. Our Sun is only one of 100 billion stars that populate our home galaxy, the Milky Way, and is by no means the oldest or youngest. This realization that the Sun is in many ways average – of ordinary mass, and common composition – implies that if the conditions of our star's formation were universal, then perhaps so are planets. We therefore want to investigate the processes of star formation throughout the Universe. In the foreseeable future, we will know details of planets only in the Solar neighborhood. In contrast, we can study the ubiquitous process of star formation over large distances throughout the Milky Way, and even through the history of the Universe by looking at distant galaxies, to understand what types of star-planet systems may exist elsewhere.

By observation, computer simulation, and theoretical calculation, astronomers have posited a star formation scenario. After a dramatic initial collapse, a protostar grows for a few hundred thousand years as gas and dust flow onto it from the surrounding cloud. A swirling flattened disk of gas and dust forms, through which additional mass flows onto the young stellar object. Eventually the new star stabilizes, the fusion of elements in its core producing energy that counteracts the compression of gravity. In broad outline, observations from the ground and from space (e.g., using the *Hubble* Space Telescope

[HST] and *Spitzer*) have verified this scenario. However, significant questions remain within this paradigm. What triggers the cloud to collapse at all? What sets the mass of the final star? How does the presence of neighboring protostars affect the material left in the disk? For how long does the disk retain material that might form a planetary system? What determines if the surrounding material forms a planetary system, a second star, or merely escapes back into empty space?

- **How do stars and disks interact?**

If star-forming cores did not spin as they collapsed, there would be no disks in which to form stars or planets. Yet, if the rotation rates were too great the disks would spin apart. Is rotation controlled by a universal process that makes all disks hospitable places for planet formation? Once the disks form, they influence the ultimate characteristics of stars, such as mass and rotation speed, while the stars drive mixing and chemical processes in the disks. X-rays and ultraviolet photons generated as stars pull in gas from the disk return to the disk and ionize its upper layers, feeding the star even faster and producing complex chemical reactions in the disk. Simultaneously, energetic photons from neighboring stars may be penetrating the disk, so the final planetary system may depend on stellar environment. The Stratospheric Observatory for Infrared Astronomy (SOFIA), *Herschel*, the *James Webb* Space Telescope (JWST), the Single-Aperture Far-InfraRed mission (SAFIR), and a future Large UV/Optical mission (generic name LUVO) will address how the presence of terrestrial and giant planets is related to disk dynamics, stellar mass, age, and magnetic activity, stellar binarity, and/or the presence of surrounding stars in a cluster.

- **When do planets form?**

Millimeter wavelength observations reveal that significant amounts of gas and dust can be left in disks around new stars, but are not yet sensitive enough to show whether this is always the case. Observations of the masses and composition of disks, from the initial massive disks surrounding young stellar objects through to the remnant disks around main sequence stars, will determine how planets get their ultimate configurations.

The most abundant gas in protostellar disks is molecular hydrogen, but this symmetric molecule is notoriously hard to observe. Future direct measurements using SOFIA, *Herschel*, JWST, SAFIR, and LUVO of molecular hydrogen via infrared emission lines or ultraviolet absorption and fluorescence will probe gas disks directly and with increasing sensitivity and angular resolution. The classic picture is that solid particles of dust coalesce early and stick to each other in collisions, slowly building a core around which a planet grows: gas giant planets do so quickly, in less than a million years, before the system loses most of its gas, and Earth-like planets do so over a longer period of tens of millions of years. This picture explains many characteristics of the Solar System, but it is now running into trouble because disks appear to dissipate too quickly to form all known planets. The eventual detection of proto-planets growing in their disks is essential to refine this picture. Initial observations could take the form of studies of the motions of H_2 gas in the disk to detect regions where gas is flowing onto pre-planetary cores.

- **Where do planets form?**

Knowledge of planetary system architectures, that is, the nature and position of all component planets, and the presence of comets and asteroids, is important for understanding the likelihood of habitable planets. Giant planets, which are unlikely to directly harbor life, dynamically constrain the orbits available for terrestrial planets. Giant planets are the older siblings – both the bullies and protectors of the terrestrial planets. How they stir up the disk determines how many comets and asteroids survive to bombard smaller worlds with either sterilizing intensity or with life-bringing chemicals. Giant planets in eccentric orbits are less likely to allow terrestrial planets to orbit stably in the habitable zone. However, gas giants might be necessary for shielding terrestrials from life-damaging impacts of comets.

One of the exciting and unexpected results of the planet searches to date is the large number of systems unlike our own. Gas giant planets have been found to orbit closer to their stars than Mercury about the Sun. Among the unsolved problems in planet formation today is not just how to form giants, but how to move them to their present locations. Some appear to have migrated large distances while others, such as Jupiter, appear to have mainly remained in place. Many gas giants also have substantial eccentricities – coming closer and further from their stars over their orbits. However, these systems exist only for a minority (10-20%) of stars, leaving open the possibility that many stars have planetary systems more like our own. Only with missions such as SIM will we obtain an unbiased view of planetary architectures.

Initial disk conditions, interactions between multiple young planets and between planets and their disks may all contribute to the final system architecture. Tracing the dynamics, densities, and temperatures of disks with high precision may betray these processes in action. If giant planets sweep up disk material, they may leave a disk devoid of the raw materials for terrestrial planets. We want to inventory the planetesimal population at the conclusion of planet formation and relate it to the architecture of the system.

The compositions and atmospheric attributes of the planets in our Solar System change dramatically from the rocky inner worlds to the hydrogen and helium dominated gas giants, to the heavy element enriched ice giants and back to the dirty ice members of the Kuiper belt. The compositions of giants will reflect their formation and migration histories.

E. How do the components of life come to reside on terrestrial planets?

Life, as we know it, depends entirely on the complex chemistry of compounds built around carbon atoms, known as organic compounds. We live on the rocky Earth with abundant silicates, iron-bearing minerals, and surface water. We now know that the Universe was not born with these materials, but that the stars themselves are the sites of their manufacture. This discovery that the heavy elements essential for life come directly from stars demonstrates the importance of understanding the creation and distribution of heavy elements and organic molecules throughout the Universe.

- **When did the Universe form the raw materials necessary for planets and life?**

The buildup of these heavy elements did not happen all at once. We have learned how these elements are made in stars and how they can be recycled into future generations of stars and potential planetary systems. At the ends of their lives massive stars explode and less massive stars slowly shed gas enriched with these heavy elements. In each cycle the abundance of heavy elements increases as the "ash" of nuclear burning in the centers of stars is added to the mix. We can roughly chart the increase in heavy elements over the generations of stars born over the 12 billion year lifetime of our Milky Way Galaxy and compare it with similar processes in other nearby galaxies. With infrared spectroscopic observations of very distant galaxies using JWST, we will soon be able to measure the buildup of elements over cosmic time. In turn, we will better understand the importance of heavy elements for the formation in the Milky Way of planets and, ultimately, life. Such observations will also trace the buildup of gas, solid-state molecules, and dust over cosmic time. This will lead us to understanding the possibility of planets and ultimately life in the Milky Way and the universe as we understand better the importance of heavy elements for the formation of planets. We already know that stars with more heavy elements are more likely to have close-in giant planets. We want to know what metal content is required for various types of planets to form and whether any particular elements are needed to make geologically-active planets such as Earth and the early Mars. JWST and the TPFs will tell us.

When and how did pre-biotic molecules necessary for life form in the history of the Universe? The infrared spectral signatures of hydrocarbon chains, hydrocarbon rings, and simple molecules (i.e., oxygen, water, carbon monoxide, methane, methanol) have been found in many regions of our Milky Way galaxy. We know that these basic components of organic molecules exist now (and likely did so 4.5 billion years ago, when the Sun and Earth formed), but at what earlier time did they come to exist in the Universe? Which materials were produced first, and when did they combine to produce the more complex molecules? Using SOFIA, JWST, and SAFIR, if we probe similar, but much more distant, galaxies when they were much younger, when the Universe was about a billion years old (less than 10% of its present age), we will see if they exhibit any hydrocarbon or ice features (redshifted to mid-infrared wavelengths) and, thus, will likely constrain the period in cosmic time when materials important for life were first created.

- **What is the origin of the interstellar medium composition?**

The atoms, dust grains, and hydrocarbon molecules released by dying stars in the Milky Way must follow long circuitous paths in order to be swept up into star forming clouds and eventually processed into materials necessary for life on planets. These newly created materials must spend large amounts of time drifting in the diffuse interstellar medium before they are eventually swept up into dense clouds of gas and dust by gravitational forces. Clouds shield these materials from damaging external radiation, allowing the carbon-nitrogen-oxygen group to form simple volatile molecules such as carbon dioxide, methane, ammonia, and water when they combine with hydrogen atoms (which are all-pervasive) and each other. This combination of volatiles, dust grains, and hydrocarbons is key to forming the chemical building blocks of life in the environments around young stars and their nascent planetary systems.

- **How do chemical/physical processes in disks create the molecules necessary for life?**

Observations from *Spitzer* are now showing that simple volatile molecules can freeze onto dust grains in circumstellar disks. Moreover, gaseous molecular hydrocarbon rings are observed to be in star-forming regions, and it is very likely that they also stick to icy dust grains in circumstellar disks. Laboratory experiments show that when these chemical mixtures are exposed to ultraviolet light – as in a disk around a young star – complex organic molecules form. Experiments have produced compounds that are needed for life, including ketones, ethers, aromatic alcohols, and even amino acids. It is logical, and now possible, to obtain infrared spectra of young stars in nearby dark clouds to see whether such materials are forming in their pre-planetary disks.

To understand the crucial steps towards the creation of life, we need to 1) conduct systematic searches for and inventory the molecules in planet-forming disks, and 2) improve our knowledge of the physical conditions in this environment. SOFIA and, particularly, JWST will be able to detect and study complex carbon-bearing molecules and water, the raw materials for life. A far-infrared and submillimeter interferometer (generically named FIRSI) will have high enough spatial resolution to see whether water vapor and more complex molecules are present in disks in regions where terrestrial planets form.

- **How are volatiles and organic molecules delivered to terrestrial planets?**

As noted above, physical processes during stellar evolution modify the disk and its constituents. Interstellar dust contains amorphous silicates, but the comets in our Solar System and dust in debris disks around other stars contain a significant fraction of crystalline silicates. These crystals must be formed in hot regions of the disk. Determining where and how these crystalline grains are produced will tell us how the disk is mixed by turbulence, inward accretion, and stellar winds, giving insight to the creation of our own Solar System, as well as others. Near-to-far-infrared spectra with high spatial resolution are necessary to trace the distribution of these important planetary constituents, requiring the *Keck* and Large Binocular Telescope (LBT) Interferometers, SOFIA, JWST, and SAFIR. As gleaned from the impact record of the early Solar System, while the disks around young stars are clearing, it is likely that these remnant rocky, crystalline asteroids and comets intensely bombard their terrestrial planets. Does this bombardment deliver the carbon-rich material to start the development of life?

Missions such as the Wide-field Infrared Survey Explorer (WISE), JWST, *Herschel*, and SAFIR that can measure the dust content of disks with time can be combined with theoretical studies to explore this phase of planetary system development. We will learn how giant planets direct material from one part of the disk, perhaps water-rich, to the inner regions where Earth-sized bodies are growing. This process may have brought volatile materials and organic compounds to the early Earth and allowed life to form on our planet.

III. Recommended Missions, Implementation Framework, and R&D Programs

A. An Integrated Program to Address the Core Questions

Discovering planets around other stars and then exploring them remotely are difficult and complex tasks, requiring many kinds of information from many sources in order to guide the search and to interpret what has been found. Determining how common Earth-like planets are in the galaxy (the frequency of Earth-like planets or $\eta_{\oplus}$) helps set mission strategies by determining the number of stellar systems that must be explored to have a reasonable chance of success. Similarly, understanding the nature of the dust disks around stars informs the theories of how systems of planets form and evolve around stars, and also helps determine the sensitivity that an observatory must have to pick out a planet from the dust background. Knowing the stellar background behind a target star tells us how difficult it will be to extract the planet signal from the confusion of other signals. This preliminary, near-term program is summarized in Figure III-1 below:

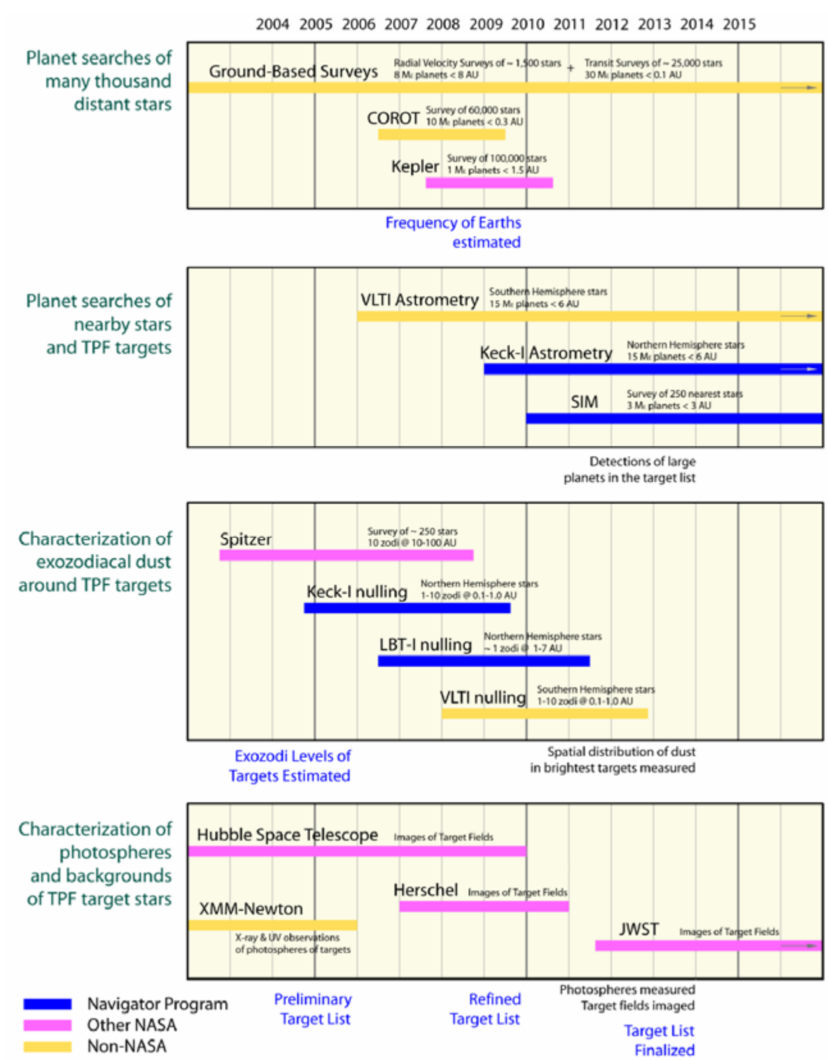


Figure III-1. The search for Earth-like planets can benefit not only from NASA's program of missions, but also from the work of scientists around the world using a variety of space- and ground-based assets.

The technology required to detect and characterize potentially habitable worlds is so challenging that no single mission can provide all the measurements needed. Nor can any one mission be as productive operating alone as it would be working as part of a carefully planned program. Consequently, the search for Earth-like planets is composed of missions that independently take intermediate observational steps, providing valuable scientific results each step along the way. These results, in addition to contributing to the overall scientific body of knowledge, are used to mitigate the risk and uncertainties inherent in the other missions, improving operational efficiencies and measurably increasing the probability of mission success.

The flagship mission to carry out a census of planets around nearby stars will be the Space Interferometry Mission (SIM PlanetQuest). SIM PlanetQuest will be the first instrument to detect Earth-like planets around the closest stars – those that we can then follow up with direct detection of light, to learn more about the planet's physical properties. SIM surveys the nearest stars and determines gross physical properties of planets such as mass and orbital eccentricity essential to establishing habitability. SIM will add critical information to our growing knowledge about the nearest stars and, thus, help to identify targets most suitable for subsequent observation by Terrestrial Planet Finder (TPF) missions. The knowledge from SIM that particular stars have (or do not have) planets of various masses and orbits, and continued radial-velocity studies, will focus the targeting choices for TPF, thereby increasing the early tempo of direct detection and characterization. A hypothetical SIM observing program might focus on the 60 most promising nearby stars. For a planet in the middle of the habitable zones of these stars, Figure III-2 provides a histogram of the cumulative number of such stars versus minimum planetary mass detectable. The potentially large number of near-Earth-mass planets SIM might detect in the habitable zone is impressive. The *Kepler* Discovery mission will provide statistics on the frequency of Earth-sized planets using distant stars, which will help set the scale of the TPF missions by suggesting how large a stellar population must be sampled to obtain data on terrestrial planets.

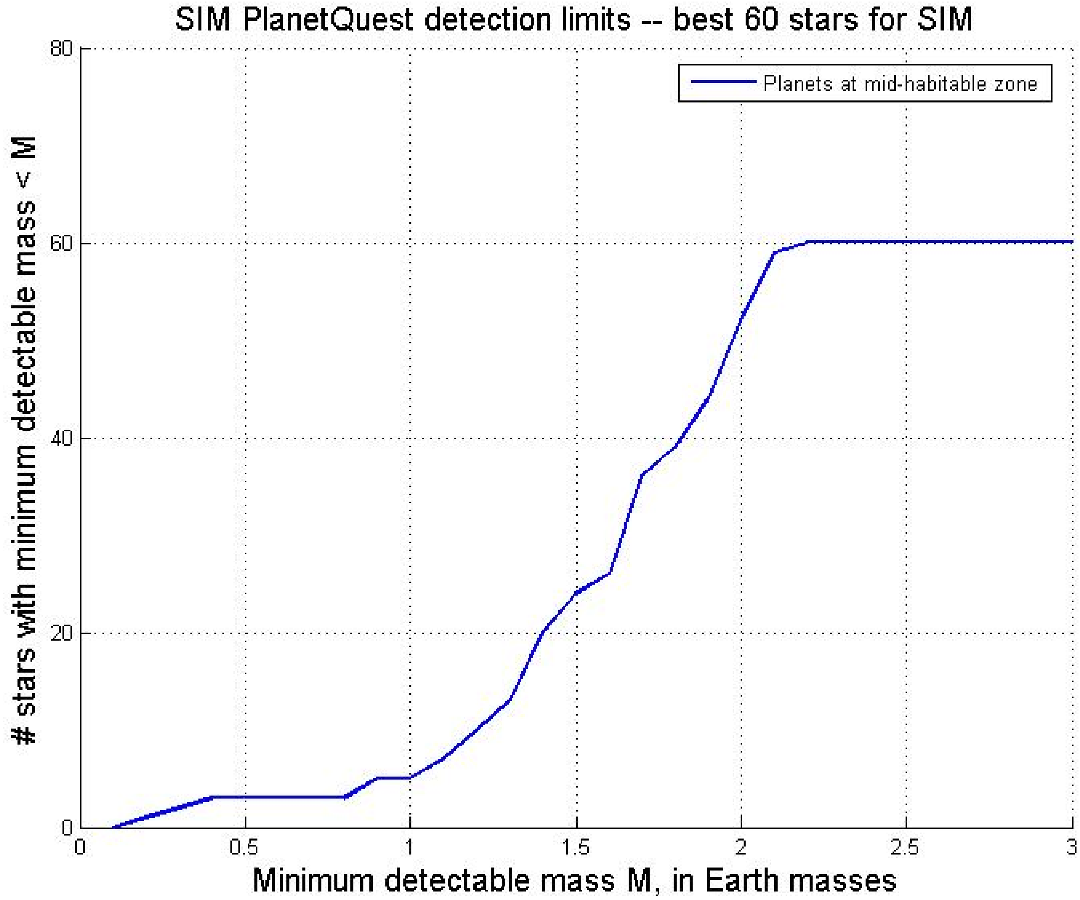


Figure III-2. SIM's capability for finding terrestrial planets. This is a histogram of the number of stars versus minimum mass for a planet in the middle of the habitable zone of the 60 best nearby stars for the SIM mission. This hypothetical observing program would concentrate ~17% of SIM time on these 60 stars. Minimum detectable mass is defined as the mass whose astrometric signature is bigger than the threshold set for a 1% false alarm probability.

Direct imaging detection and spectroscopic characterization of nearby Earth-like planets will require the Terrestrial Planet Finder (TPF) missions. The first, the TPF Coronagraph (TPF-C), planned for launch in 2014, will suppress the light of the central star to unprecedented levels, allowing it to search for terrestrial planets in ~120 nearby planetary systems, and thoroughly study 35. TPF-C will be followed by the TPF Interferometer (TPF-I) about five years later. TPF-I will operate in the mid-IR, will search for terrestrial planets around approximately 500 stars, and will characterize all of those it finds.

Once a terrestrial planet is detected, TPF-C and TPF-I will determine which planets have conditions suitable for life, e.g. a warm, wet atmosphere, and which, if any, show global signs of life, e.g. an oxygen-rich atmosphere due to the effects of photosynthesis. Theoretical, laboratory, and field studies are already under way to learn which "biosignatures" —identifiable features in the spectrum of the planet's light—can reveal the presence of life on a distant planet. This research will guide the requirements for the Terrestrial Planet Finders, and help in the design of future telescopes, such as Life Finder.

Existing infrared telescopes, such as *Spitzer,* the LBT-I, and the *Keck* Interferometer, will investigate exo-zodiacal dust clouds for both their intrinsic scientific interest as by-products of planet formation and to help optimize the target list for TPF. Future mid- to far-infrared telescopes such as SOFIA, JWST, *Herschel*, and SAFIR will allow us to determine the evolving location and composition of dust in planet-forming disks. Observations of ice and organic compounds in disks with JWST, TPF-C, and SAFIR with spectroscopic capability can be combined with theories of organic chemistry, volatile processing and orbital dynamics to place constraints on the formation and evolution of pre-biotic compounds, and their delivery to terrestrial planets.

Once TPF-C and TPF-I have completed their investigations of the characteristics and habitability of Earth-like planets, and made first-order attempts to detect the most obvious global biosignatures, the next important scientific step will be a more thorough and capable search for life by Life Finder on a larger number of planets. After that, a far-future Planet Imager can be envisioned to obtain coarse images of exoplanets to detect their basic land and ocean surface features. Such a mission would be extraordinarily difficult and expensive, probably requiring multiple launches of 10-20 m telescopes whose light could be combined interferometrically. Planet Imager will continue to be evaluated and refined as the search for other Earths proceeds over the next decades. The overriding consideration for the long-range future of this mission concept is the will and commitment of the Nation, or of the community of space-faring nations, to invest the resources that will be required for such an epochal exploration.

B. Implementation Philosophy

The explorations described in this Roadmap will require the development of missions with unprecedented capability. The challenges this presents have led to adoption of certain philosophical principles in the implementation of the Universe investigations. These include:

- The most challenging investigations will be carried out through strategic missions identified and endorsed through the strategic planning process and the National Academy of Science Decadal Survey of astronomy. These strategic missions will be led by NASA flight centers, with science teams, key investigations and instruments drawn from the broad scientific community through open peer-reviewed competition.

- Strategic missions will be initiated through an extended pre-formulation (pre-Phase A) period where all of the high-risk technologies will be developed before the mission is allowed to proceed into the higher cost-rate period of formal formulation and implementation. This provides an essential cost-risk mitigation strategy that has served NASA well.

- Where important scientific investigations can be accomplished without significant new technology development, and without excessive development risk, a series of competed PI-led mission opportunities at a variety of cost levels will be invoked. These investigations may be identified through the strategic Roadmap, or may be proposed *ab initio* by the PI. Mission lines exist at low- (~$200M Explorer Program), medium- (~$400M Discovery Program) and high- (~$600M Universe Probes) cost levels. The proposed Universe Probe line of the Universe Division would be a competed mission on a scale between a Discovery and a Strategic mission that is an essential component of a well-balanced program that can take advantage of new developments as they arise.

In order to focus the complex relationships of the scientific and technological activities involved in carrying out the science described in this Roadmap, NASA has organized the implementation of closely related missions of extrasolar planet exploration into the Navigator Program: Exploring New Worlds. Navigator is responsible for conducting the precursor and supporting science activities, technology development and implementation of these missions. Figure III-3 below encapsulates the implementation plan for this integrated Roadmap, the place of the Navigator Program within it, and very approximate timelines.

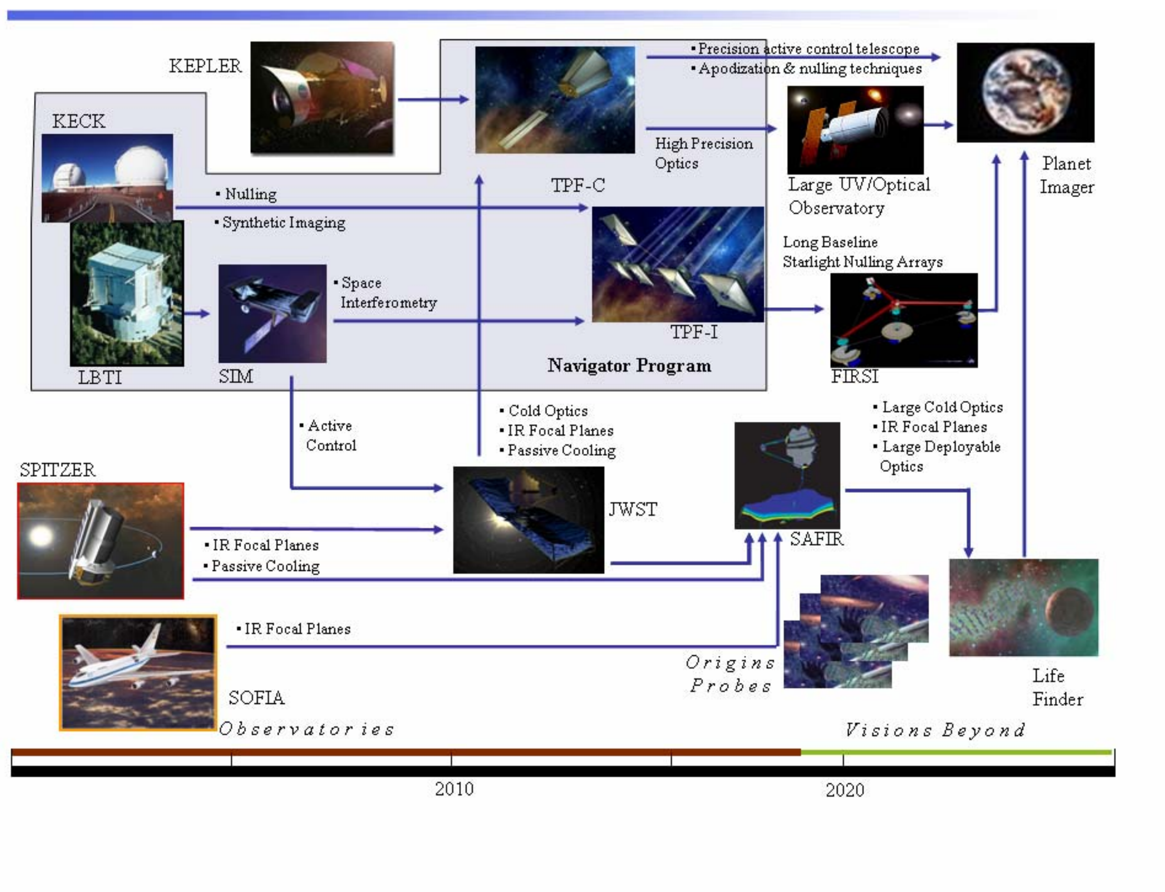


Figure III-3. Mission implementation roadmap, including the responsibilities of the Navigator Program and approximate timelines.

C. Ground-based Initiatives, R&A, Theoretical Challenges, and Astrobiology

With bigger telescopes, more observing time, and better instruments, the ground-based Doppler method of planet detection is poised to achieve precision better than the existing 1 m/s. For comparison, an Earth-mass planet at 1 AU induces a wobble of 0.1 m/s in a solar-mass star. Though Earth-like planets in the habitable zone around a solar-mass star are not currently detectable, Doppler precision is likely to be improved with superior spectrometers and spectroscopic analysis. Furthermore, low-mass planets could preferentially be found in the habitable zones of low-mass stars. The allocation of more telescope time permits averaging over photospheric turbulent "jitter" to approach a precision of 0.3 m/s, rendering detectable planets with masses down to 3 Earth masses orbiting in the habitable zones of solar-mass stars. The US government investment in *Keck* and in other ground-based telescopes will be particularly valuable for continued Doppler work.

NASA should remain vigilant and support new technologies that are still under development, such as astrometry at the south pole, microlensing from space, and transit-planet spectroscopy with *Spitzer*. This Roadmap also requires continued technology development for coronagraphs, ultra-lightweight, high-contrast optics, formation flying and interferometric nulling, detectors, and improved Doppler instruments. Furthermore, the theory of planet formation is poised to make predictions about the occurrence and properties of rocky planets, constrained by the properties of the observed giant exoplanets. To support TPF, theoretical work on the formation of rocky planets, their dynamical evolution, and the diversity of their interiors and atmospheres should be strongly supported. Theoretical and laboratory work on the origin and evolution of the atmospheres of rocky planets, both with and without biological feedback, should be vigorously pursued.

Detecting and characterizing extrasolar terrestrial planets poses both considerable technological *and* scientific challenges. While substantial investments in large space-based telescopes will be required to make significant progress in this field, the ultimate scientific payoff from these missions will require not only the technological capabilities, but a strong scientific foundation from an active, interdisciplinary scientific community. Both precursor and supporting observations from space-based and ground-based telescopes, as well as a rich program of theoretical and interdisciplinary research will be needed. Theoretical, laboratory, and field research will provide end-to-end mission support by supplying crucial new ideas, context and information relevant to mission planning, design and science priorities, and by providing the expertise and tools to convert the hard-won spacecraft measurements into new scientific understanding. NASA will build and maintain this interdisciplinary science community via competed R&A programs, of which the TPF Foundation Science program, NASA Astrobiology Institute, the Astrophysics Theory Program, the Origins of Solar Systems Program, the Astrophysical Data Program (ADP), and the Interdisciplinary Exploration Science program are current examples. Theoretical and multidisciplinary scientific research should also be integrated into the fundamental mission design to address scientific challenges that are critical to the mission's key goals.

To meet our objective to find and characterize habitable planets around other stars, we will need theoretical research and modeling to understand the plausible range of solar system architectures and planets that we may find, to understand the relationships between the host star and environments of its orbiting planets, and to interpret the photometric and spectroscopic signatures of life. Modeling can be used to understand the formation and evolution of habitable planets, including volatile delivery throughout a planet's lifetime, and to explore how planetary processes affect habitability over time. The interiors and atmospheres of rocky planets having masses 1-10 Earth-masses are not represented in our Solar System, and therefore require modeling to predict their characteristics. The modeled characteristics will inform our understanding of how to best discriminate observationally between planets of different compositions and stages of development. To that end, modeling is also required to understand the detectability of planetary characteristics in the low-resolution, full-disk spectra that will be available to the Terrestrial Planet Finder and Life Finder missions.

The relatively new field of astrobiology uses intrinsically interdisciplinary approaches to study the origins, evolution, distribution, and future of life in the Universe. This fundamental research will allow us to explore biosignatures in great detail, both theoretically and by obtaining field or laboratory data, to better understand those signs of life that might be remotely detected in the spectrum of another planet, especially for habitable planets that differ from our own modern Earth, in age or composition. This research must also identify potential "false-positives," the non-biological planetary characteristics that mimic biosignatures. The results of this research will help determine the design and characterization strategies for the TPF and successor missions, and the breadth of the research will enhance mission success by increasing our overall likelihood of detecting and correctly interpreting biosignatures in the context of extrasolar terrestrial planet environments.

IV. Key Milestones and Decision Points

A. Milestones

Accomplishing the mission set recommended in this Roadmap requires both an ongoing interaction with the developing body of scientific knowledge and technological achievements along the way. Scientific knowledge feeds into the design concepts and the scaling of the system designs. Technologies needed by a mission must be developed to the point where feasibility is demonstrated with a high degree of confidence by the time the mission enters Phase A, where the design concept is set. The technology must be demonstrated in terms of performance in a flight-like environment before the mission can proceed with implementation. The milestones summarized in Figure IV-1 will provide input at key decision points and opportunities to mitigate risk and adapt to new findings.

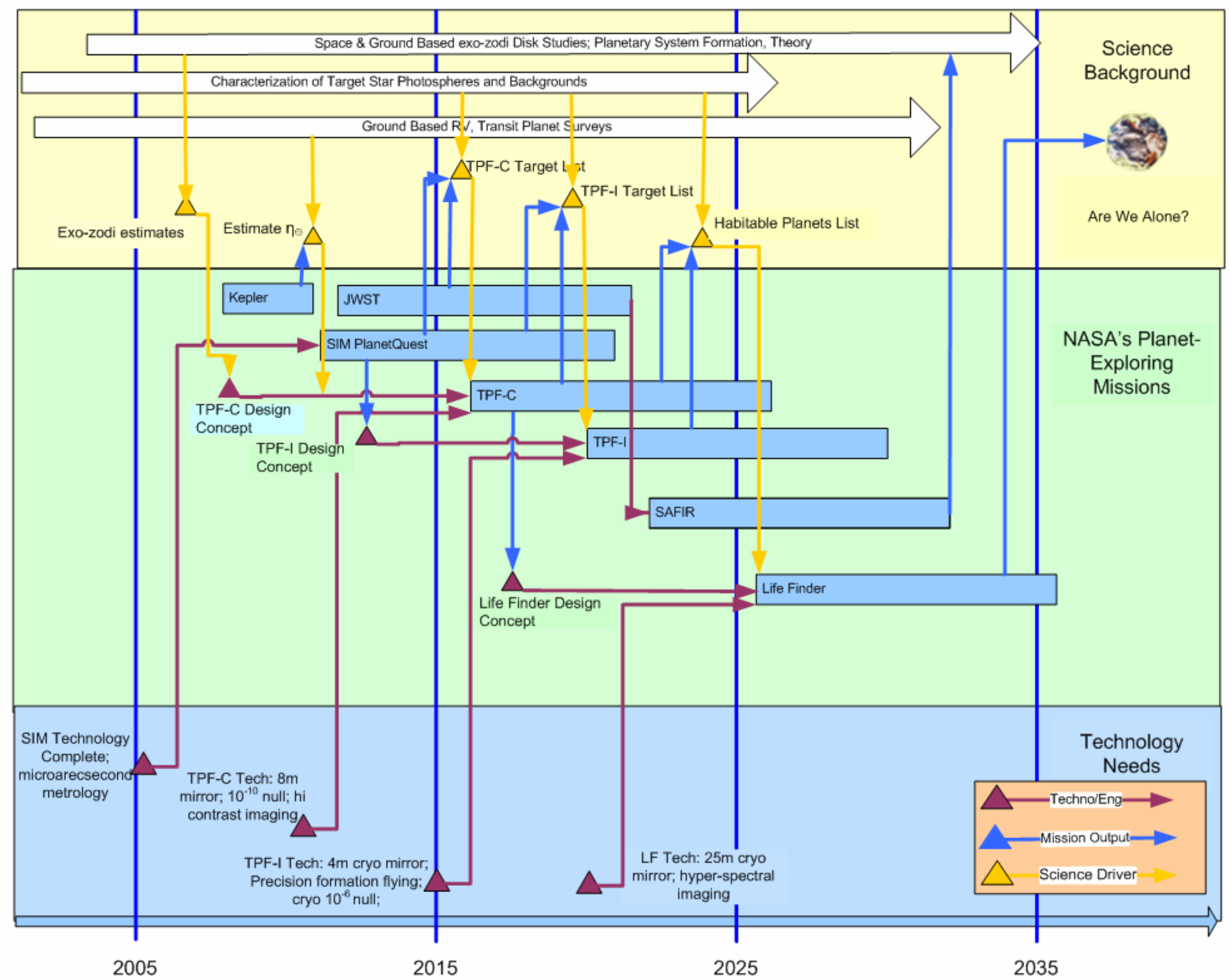


Figure IV-1. Key milestones on the road to other worlds.

The Navigator Program has been carrying out a focused set of technology development activities to enable the missions to explore exoplanets. Examples of milestones concerning the integrated program to discover, explore, and characterize exoplanets that have been, or soon will be, met include:

1. Development of interferometric techniques using the Palomar Testbed Interferometer for application on the Keck Interferometer and SIM PlanetQuest. (**Complete**)
2. Implementation of initial interferometric operational capability (fringe visibilities) between the two Keck 10-m telescopes. (**Complete**)
3. Development of techniques and ground testbeds to demonstrate ultra-precision metrology and system stability to a picometer accuracy for SIM PlanetQuest, at both component and system-level. (**On Schedule**)
4. Development of 10^{-10} contrast ratio for visible nulling for TPF-C, and demonstration of 10^{-9}. (**On Schedule**)
5. Development of 4-way beam combination IR nulling for TPF-I and demonstration at 10^{-5} level. (**On Schedule**)
6. Development of robust ground testbed demonstration capability for precision formation flying to enable TPF-I as well as a number of other future missions in astronomy. (**On Schedule**)

Conduct advanced telescope searches for Earth-like planets and habitable environments			
	Phase 1: 2005-2015	**Phase 2: 2015-2025**	**Phase 3: 2025 +**
Planet Detection	a) Measure the frequency of Earth-like planets in a statistically representative sample [COROT, *Kepler*] b) Radial velocity surveys detect additional Jupiter analogs and nearby planets with less than 10 M_{earth} [Ground] c) First SIM planet detections	a) Astrometric detection of M>3 M_{earth} planets in habitable zone within 10 parsecs [SIM] b) Photometric detection of M > 0.5 M_{earth} planets in stellar habitable zone within 10 parsecs [TPF-C] c) Photometric detection of M > 0.5 M_{earth} planets in stellar habitable zone within 100 parsecs [TPF-I]	a) At least an order of magnitude increase in the number of directly-detected terrestrial planets [LF] b) Direct detection of moons in nearby extrasolar planetary systems [LF]
Planet Characterization	a) Measure atmospheric spectra of hot Jupiters seen in transiting events [Ground, HST, *Spitzer*, JWST] b) Measure spectra of brown dwarfs and giant planets [JWST]	a) Measure Mass [SIM] b) Measure radius and surface temperature [TPF-C+TPF-I] c) Detect basic atmospheric composition and presence of clouds [TPF-C+TPF-I] d) Determine gross surface properties [TPF-C, TPF-I] e) Detect new classes of planets [SIM, TPF-C, TPF-I] f) Detect provisional indications of life [TPF-C, TPF-I]	a) Confirmation of biomarkers [LF] b) Search for life on a larger sample of planets [LF] c) Search for a variety of different metabolisms [LF] d) Enhance characterization of planetary systems [LF]
Planet Formation and Habitability	Observe the formation and evolution of stars, galaxies, and planetary systems, from the first luminous objects to debris disks in our own neighborhood [*Spitzer*, SOFIA, *Herschel*, JWST]	Observe the development of conditions for life, from the first release of the chemical elements in the first stars, through the formation of protoplanetary disks, to the chemistry and physics of the Solar System [SOFIA, JWST,SAFIR]	a) Observe proto-planetary disks with the resolution needed to detect Earths in formation [FIRSI] b) Trace the chemical evolution of the early Universe [Large UV/Optical Imager]

Table IV-1. Expected scientific achievements in the near-, mid-, and far-term of this Roadmap and the missions that will accomplish them.

B. Potential Decision Points

The nominal architecture of the program of missions in this Roadmap incorporates the minimum mission set necessary to conduct a complete, but initial, exploration of planets around other stars up to and including the search for signs of life. It starts at the simplest point – a look at a very large sample of stars, far away, to see how many have planets and how many of those could be Earth-like (*Kepler*). While most of these will not be stellar neighbors, they comprise a large sample that can be observed together to determine overall exoplanet statistics. The program then goes on to provide the necessary survey of gross physical properties of nearby planets and their systems (SIM PlanetQuest). Following SIM, TPF-C and TPF-I will conduct mutually complementary and confirming spectral imaging investigations to identify potentially habitable planets and to make a first search for signs of life. Finally, Life Finder will execute a refined and thorough spectroscopic investigation of the most promising candidates determined by TPF, providing robust confirmation of signs of life, as well as searching for different types of life on a larger sample of terrestrial planets. The scale and timing of these missions are predicated on an assumption that Earth-like planets are modestly common – i.e., the fraction ($\eta_\oplus$) of Sun-like stars that have Earth-like planets (both in terms of size and position in the habitable zone) is greater than or equal to 10%.

Each of the milestones for scientific knowledge or technological capability represents a decision point in terms of design parameters for the particular mission that is affected. However, there are also events that could affect the overall architecture of the program. Surprising early discoveries of very nearby terrestrial planets might be an opportunity to solicit proposals for rapid-development, low-cost missions designed to study just that planet. Well-developed methodologies for such solicitations, coupled with emerging technologies for rapid, low-cost optics development, will enable agile responses to such serendipitous discoveries.

What if the key assumption that $\eta_\oplus \sim 10\%$ should be wrong? Or what if one of the missions in the sequence fails for technical or programmatic reasons? At the program-level, there are a few key eventualities for which alternate architectural paths have been identified. These are represented in Figure IV-2.

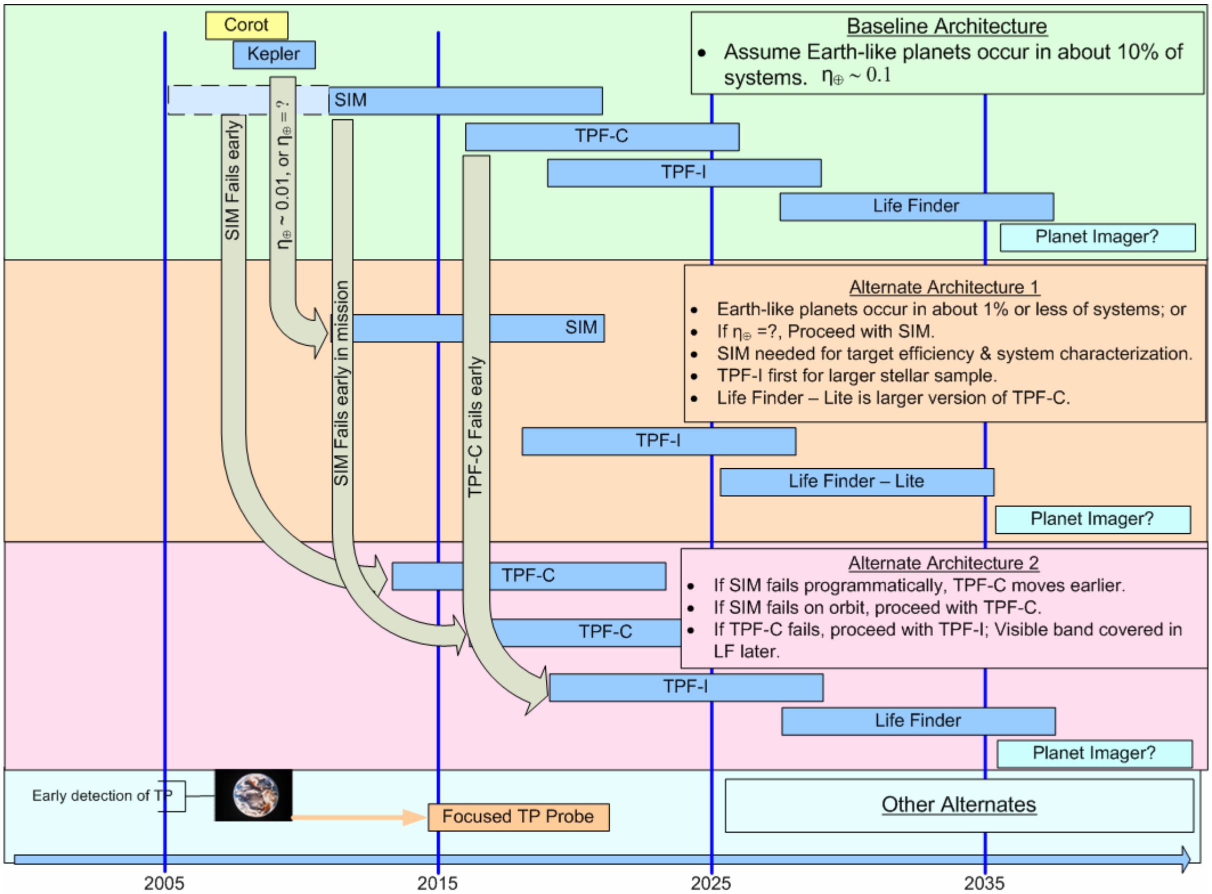


Figure IV-2. Some alternate architectures, branch points, and options.

None of the missions in the program is a <u>necessary</u> precursor to others in the early part of the sequence; however, the sequence represented in the baseline architecture is important because the knowledge gained from one mission helps subsequent ones. For example, in the case of SIM, it not only provides vital data on physical properties of exoplanets, but can enhance the early targeting efficiency for both TPF-C and TPF-I. In particular, SIM discoveries can focus subsequent TPF targeting choices to ensure that the practical yield of terrestrial planets that are well-characterized by TPF-C is optimized during TPF-C's finite lifetime, thereby increasing the scientific return of that mission. Similarly, TPF-C images combined with SIM-derived orbits can help interpret TPF-I data. Later in the sequence, if, for example, no habitable planets had been found, there would be no scientific driver to proceed with a Life Finder (although observatories of comparable capability would certainly be needed for other scientific purposes).

1. If *Kepler*/COROT show that Earths are common or rare?

A rapidly growing dataset on exoplanets is leading astronomers to feel increasingly comfortable with the expectation that at least 10% of solar-type stars will have Earth-like planets. The sequence and scale of the baseline mission architecture is predicated on this assumption.

Should the early transit missions, *Kepler* and COROT (a mission of the French space agency, CNES), show that the fraction is much lower, say around 1%, it will call for a reexamination of the sequence. In particular, SIM would still proceed, not only because it would already be nearly ready for launch, but also because its ability to probe a fairly large number of nearby stars in a target-poor environment would enable the best possible determination of the target list for TPF-C or TPF–I to pursue. Consideration would then be given to deferring further development of TPF-C, and instead accelerating TPF-I, with its long baseline able to achieve angular resolution at larger distances, and, thereby, able to investigate a larger stellar population. These data would provide the IR coverage of the observed systems, and would also provide information useful for targeting of a subsequent visible band mission (LUVO). In this scenario, Life Finder would be accelerated as a "LF-Lite" mission, taking advantage of advances in large aperture space telescope technology available by then. This is depicted as Alternate Architecture 1 on Figure IV.2.

2. If SIM-PlanetQuest can not do better than 5 μas?

Should the on-orbit performance of SIM PlanetQuest fall significantly below its design value, it could still greatly augment radial-velocity studies in characterizing extrasolar planetary systems, as well as carry out groundbreaking programs in general astrophysics. However, its value as a TPF-C precursor in identifying target stars and target epochs for viewing Earth-like planets (e.g., knowing when a target planet is visible at elongation) would be severely diminished. At that point, the best response would likely be a replanning of the TPF-C observing sequence to compensate for the greater uncertainty of targets and timing of observation.

3. If, for whatever reason, some mission does not proceed?

A number of alternate routes and off-ramps are available in the case of mission deferral or failure. All of these assume that the cause of the failure is known, and has been factored into subsequent developments to preclude a repeat of the same failure. If either of the early transit missions (COROT or *Kepler*) fails, the other provides a backup. If for some reason both fail, then we are proceeding with a large uncertainty in $\eta_\oplus$. While knowledge of the statistics of planets around a distant stellar population would be valuable for planning the TPF missions, SIM would not be making statistical studies of $\eta_\oplus$ for the nearby stars. Rather, it would determine directly what TPF needs – the locations and properties of planetary systems around nearby stars. So in this case, SIM would proceed. Depending on SIM's early results, if $\eta_\oplus$ should turn out to be ~1%, then consideration would be given to switching between TPF-C and TPF-I, as case 1 above, since TPF-I has a larger range.

If for some reason SIM does not proceed on the current schedule, then TPF-C could be moved a bit earlier. If SIM has proceeded on the current schedule, but for whatever reason fails early on orbit, one option would be to reset and build another SIM; however, since TPF-C will be well along on its development path, it would be more economical to proceed with TPF-C and rely on its imaging capability to provide snapshots of the most likely stellar systems for subsequent use by TPF-I. However, the need for masses is so central a feature of our Roadmap, that an astrometric mission such as SIM must still eventually be done.

If TPF-C fails early, then the most logical thing would be to proceed with TPF-I and to make the subsequent Life Finder mission an optical mission. If TPF-I should fail early, Life Finder could still proceed, targeting those planets identified by TPF-C as satisfying the conditions of habitability, but Life Finder would then be an infrared mission. In any case, data in both the infrared and the optical are necessary for the complete characterization of terrestrial planets that is a central cornerstone of this Roadmap.

4. If there are surprising discoveries?

If $\eta_{\oplus}$ is found to be one or greater, the closest Earth-like planets could be only a few parsecs away. As a result, the scientific emphasis of the program might shift to emphasize characterization of these nearby planets. Even though the requirements on angular resolution needed to survey more distant habitable zones could be relaxed, large apertures would still be required for spectroscopic analysis. While SIM and TPF-C would proceed as planned, the TPF-I architecture might change from the free-flying spacecraft needed for higher angular resolution to a shorter-baseline, connected structure with a large collecting area for spectroscopy.

The discovery of a terrestrial planet around a very nearby star (such as α Centauri) through a "lucky transit" or other such event could trigger a call for a competed mission designed to study just that planet. "Universe Probes" can be part of a "rapid-response" strategy to exploit opportunities afforded by such surprising discoveries. Invoking a low-cost architecture, such as a pinhole camera, enabled by emerging low-cost rapid-fabrication optical technology, would bring to bear a focused mission to study the new planet in parallel with the ongoing strategic flagship missions designed to look much more broadly for other planets in our neighborhood.

5. Role for smaller, competitively-selected missions and new technology

The path towards characterizing planetary systems includes important roles for smaller, competitively selected missions. Technological breakthroughs already in sight are the lifeblood of this Roadmap, but not all can be predicted in advance. Some additional possibilities include improved methods for suppressing starlight in coronagraphs and nulling interferometers, improved concepts for operating SIM to improve its accuracy, or improved detector technology. Such improvements would enhance the performance of the planned mission sequence, or could be incorporated in competitively selected smaller missions, but do not change the basic scientific approach or requirements. The technical challenges facing TPF-C and TPF-I could be tested at reduced risk in the space environment with smaller scale, space-borne missions: either an optical coronagraphic imager or an structurally connected infrared interferometer. Both have been discussed and/or proposed for $350-450M Discovery line, either as US-only, or in conjunction with other countries. A space telescope with an aperture of 2 meters, outfitted with adaptive optics and a coronagraph, can't detect Earths, but can detect analogs of Jupiter and Saturn orbiting between 5-20 AU from nearby stars. Similarly, a nulling interferometer operating at 3-5 microns over a 10-m baseline could study infrared emission from hot Jupiters. In both cases, a modest spectrometer could detect many of the molecular constituents of the atmospheres of giant planets, yielding insights about the chemical composition and origin of these planets. The light rejecting technologies by which these telescopes would block the starlight would be similar to those necessary for TPF-C or TPF-I, providing valuable technical insights about the more difficult goal of detecting Earths. A proof of concept for either approach might be feasible at the cost of a Discovery-Class mission.

V. Technological Dependencies, Linkages, and Infrastructure Requirements

A. Key technology requirements for each mission concept

In this chapter (which should be read in conjunction with Chapter VI on "Critical Inter-Roadmap Dependencies"), we provide a more detailed summary of the technology requirements and plans for missions that advance the science of exoplanets, from discovery, to understanding their formation and evolution, to determining the conditions for life, back to the beginning of time. Many of the key technologies have been reviewed and presented in the Advanced Telescopes & Observatories Capability Roadmap, but there are also dependencies on the launch vehicles, propulsion, communications, and servicing Capabilities Roadmaps, as articulated in Chapter VI.

The missions in this Roadmap are entirely dependent on new technologies, largely enabled by the application of computer modeling and closed-loop control systems to correct errors and allow the use of lightweight optics. In addition, the critical detector systems are dependent on investments made over many years, and require continued funding.

There are four core missions currently under development, ***Kepler*,** **SIM, JWST**, and **TPF-C,** that will take us through the 2015-2020 time frame. There are then two missions specifically devoted to planet finding and characterization that are undergoing conceptual development, **TPF-I** and **Life Finder**; these missions are critically dependent on the technologies to be developed during SIM and TPF-C. A parallel thread of our Roadmap dealing with the formation of planets and stars and protostellar/protoplanetary disks is accomplished not only by **JWST**, but by the strategic missions **SOFIA** and **SAFIR**. In the distant future, a far-infrared and submillimeter interferometer ("**FIRSI**") could provide high-resolution imaging of an unprecedented character. These would be powerful tools to understand the formation and evolution of planetary systems. Also, a future general-purpose **Large UV-Optical telescope** would extend the Hubble Space Telescope's (HST's) observations of planetary systems. These mid- and far-IR missions and UV-optical missions are also strong components of the SR#8 ("Universe") scientific area with explicit dependencies. We now proceed to a mission-by-mission discussion of technological linkages and dependencies.

The ***Kepler*** Discovery mission will view about 100,000 distant stars to discover terrestrial planets via dimming of the star because of the planet's transit of the star. This mission requires photometry at one part in 100,000. Since the occultations typically take 4-8 hours, the spacecraft has three multi-hour driving requirements: the pointing jitter must be 100 milliarcseconds or better, the optical system must be sufficiently stable in order to have a stable point spread function, and the CCDs must have stable relative performance. The hardware development is proceeding to plan and all of these driving requirements will be met or exceeded.

The **SIM** mission will find planetary systems around nearby stars by detecting changes to the stars' proper motions due to planetary perturbations. There are two very difficult requirements that must be met. The first is picometer metrology, which will be accomplished interferometrically. The second is end-to-end verification of system performance on the ground in 1-g; modeling will need to be developed to a new level of sophistication so that the hardware subsystems will be verified, and then the subsystems will be tied together via the system model to provide the confidence needed before committing to launch. These capabilities must be developed on SIM in order to confidently proceed into TPF-I. In fact, metrology and sophisticated modeling are required for all of the future missions that rely on interferometry and/or long-baseline/multi-spacecraft optical systems. SIM will validate this technology and modeling to a high degree in the flight environment in preparation for these still more challenging missions. The related European astrometry mission, *Gaia,* will not have the sensitivity to measure the masses of Earth-like planets.

The **JWST** mission will provide imaging, spectroscopy, and basic coronagraphic capabilities at wavelengths from 0.6 to 28 microns. JWST requires deployment of precision optical components, and it has benefited from the development of mid-infrared detector arrays and the passive cooling technologies of *Spitzer*. Key technologies being completed for JWST include the ultra-light deployable segmented beryllium primary mirror, wavefront sensing and control, a multilayer deployable sunshield, radiative cooling to the 30 – 50 K level, advanced large format IR detectors of HgCdTe and Si:As with much lower noise levels than achieved before, micro-shutter arrays for multi-object spectroscopy, and a mechanical cryocooler to cool the mid-IR detectors to 7 K. JWST decided to use a cryocooler to reduce mass, and will fund one design for flight. Cryocoolers are required for most of the IR missions in this Roadmap. They have been developed at industrial labs worldwide, and at NASA centers. The ACTDP (Advanced Cryocooler Technology Development Program) held competitions and selected winners for further development, aiming to support JWST, Con-X, and TPF-I. The design for the JWST cryocooler may be sufficient for TPF-I, but future far-IR missions and Constellation-X (SR#8) will need additional stages to reach temperatures much below one Kelvin.

The **TPF-C** mission (Terrestrial Planet Finder-Coronagraph) will directly detect (at visible wavelengths) Earth-like planets around nearby (~30 light-years) Sun-like stars. There are several driving requirements for this mission. The brightness ratio between the visible star and its reflected light from the planet is 10^{10}, while the angle subtended between the star and Earth-like planet will be on the order of 100 milliarcseconds. The flux from an Earth-like planet is estimated to be roughly 0.05 photons/m^2sec over the full visible wavelength band from 0.4 to 0.9 microns. Therefore, a mirror of ~ 25 m^2, with a 5 nanometer rms surface, and with 20-picometer wavefront control will be required to achieve a flux of about 1 photon/sec with sufficient contrast and signal-to-noise ratio to actually "see the planet." Innovative processes to fabricate low-scatter surfaces and precision masks are some of the many advanced telescope technologies underway today. TPF-C will inherit a portion of the SIM optical bench and structures metrology that gives 200-picometer precision. A monolithic mirror is required because a segmented mirror's edge-scattering effects will degrade the contrast ratio. ITT/Kodak is under contract to develop techniques for the large lightweighted mirror and for the surface finish. (See section B below for further discussion of the optical technology readiness.) Improved detectors in the visible (and, possibly, in the near-infrared) are essential for spectroscopy of the detected objects. The scientific benefits of array detectors that detect individual photons would be immense, and there are promising ideas that could succeed with continued funding.

The **TPF-I** mission (Terrestrial Planet Finder-Interferometer), best done jointly with ESA as TPF-I/*Darwin*, will detect Earth-like planets around nearby Sun-like stars, but will have a greater range than TPF-C. This mission builds on SIM technologies in very important ways in that nanometer metrology will be used, but at longer wavelengths of 6-17 microns. Such wavelengths ease the requirements somewhat for nulling of the radiation from the Earth-like planet's star. The current baseline configuration of this mission is 5 spacecraft, one combiner and 4 collectors with about 4-meter diameter apertures in a linear array, with a maximum separation of a few hundred meters. JWST technologies are basic to the optics, detectors, and cooling. TPF-I is the first planned mission that requires precise formation flying and will require perfect precision formation flying techniques so that the light from its independent telescopes can be combined and controlled to an accuracy of much less than one wavelength. In fact, TPF-I, in addition to requiring large aperture telescope technology, will need that special set of technologies unique to interferometry, which includes formation control algorithms, optical beam combiners, micro-Newton thrusters, laser metrology, and intersatellite navigation. This set of capabilities will also be needed for the Black Hole Imager and Big Bang Observer missions of the *Beyond Einstein* program highlighted in SR#8.

The **Life Finder** mission will require many more photons than TPF-C to perform robust spectral analysis of biological signatures. There is now discussion among scientists as to whether visible or mid-infrared spectroscopy will yield the best spectral evidence for the existence of life. We expect that a roughly 100 times increase in aperture area will be needed over TPF-C or TPF-I to provide unambiguous identification of biological markers. The technical requirements will depend on the scientific results from TPF-C and TPF-I, and in particular on the then-known characteristics of the most observable targets. The Life Finder and the Large UVO (LUVO) telescopes will build on the success of the TPF-C telescope technologies to produce a telescope system with an aperture in excess of 10 meters diameter that will need to be precision-deployed and autonomously aligned. In any case, the much larger apertures required are impossible with today's technology, and a significant effort for a long period of time will be required. On the other hand, other Government agencies (NRO, DOD) also have requirements for very large apertures, and there is no fundamental reason that computer control could not manage such large apertures. The Life Finder is the first in this series of missions that might require complex in-orbit assembly and test, and would strongly benefit from technology development in remote manipulation, robotic servicing, and even human servicing. Life Finder would also benefit strongly from larger launch vehicles, as well as technologies that reduce vibration and acoustic disturbances in the launch environment. These technologies would also benefit earlier large observatories.

The **Planet Imager** mission will attempt to image roughly 25 pixels across each dimension of a planet at 10 parsecs. This may require about 12 spacecraft separated by an average of 100 km, each with a 10- to 20-meter diameter primary mirror. The success of this mission hinges critically on technology to achieve extremely high-contrast images, such as is being developed for TPF-C, and the formation flying capabilities of TPF-I and Life Finder. While there is no law of nature preventing such a mission, we have no clear path for the needed technology. Nevertheless, the extraordinary cultural importance of such a project and its role as a long-term technology driver will keep it in the Vision until it can be completed by future generations.

Mid- and Far-IR missions. The Stratospheric Observatory for Infrared Astronomy (**SOFIA**) will have a 2.5-meter airborne telescope that is optimized for infrared to submillimeter observations. SOFIA will observe dust, gas, and molecular ices in the envelopes and planet-forming disks around young stars, as well as other obscured regions in the local Universe. SOFIA is nearing the completion of its development, and it will operate until after 2020. Many of its 9 first generation science instruments have technologies related to *Spitzer*, JWST, and *Herschel* instruments, and its instruments will be frequently updated with new capabilities that will allow SOFIA to maintain state-of-the-art performance. SOFIA has also developed some new detectors for its instruments, and it will serve as a very versatile platform to develop and test instrument technologies (primarily detectors and coolers) that would otherwise have to be tested in space. A vigorous instrument program will ensure that SOFIA maintains state-of-the-art instruments and develops new technologies upon which future missions such as SAFIR can build.

The Single Aperture Far-InfraRed (**SAFIR**) mission will study star and planet formation with imaging and spectroscopy. Its telescope is expected to have an aperture of about 10 meters, and it will observe emission from molecules and grains at wavelengths from 20-500 microns. Its telescope will be both actively and passively cooled to below 4K, requiring the development of long-life mechanical coolers that operate at low temperatures and have large capacities. SAFIR will benefit from the passive cooling architecture of JWST, which will also find application in the Life Finder and future missions. SAFIR will need large format arrays of far-infrared and submillimeter detectors, prototypes of which are to be developed on SOFIA. However, SAFIR will still require an aggressive development program of its own for mid- and far-IR detectors.

Advanced far-infrared and submillimeter interferometric missions (such as the generically named **FIRSI)** are also being studied for development after SAFIR. These missions would require unique technology development for advanced cryocoolers, lighter-weight and lower-cost optics, and advanced detectors. Unlike detectors and coolers for shorter wavelengths, there are no funds outside of NASA for development in the far-infrared. As a result, these missions are critically dependent on NASA technology development funding.

The **Large UV-Optical Telescope (**generically named **LUVO)** is also of importance to this Roadmap. Indeed, HST, a UV/optical telescope, is the only telescope that has observed a spectral line of another planet. The need for a separate large UV-Optical telescope might depend on the ability of TPF-C to carry out science outside the specific coronagraphic objectives.

Alternative Concepts and Competed Missions are still under consideration for future strategic missions, as well as the less-costly Universe Probe missions. NASA has supported these through HQ competitions, TPF project-managed competitions, and the NIAC. As an example, we cite the idea of an external coronagraph, with a blocking body or a pinhole on a separate payload, flying in formation on the line of sight between the telescope and the star, which might be brought to bear as a single-planet deep study mission in response to a surprise discovery of a nearby terrestrial planet (see Chapter IV.B.4 under "Decision Points"). We endorse the continued search for new ways to accomplish the goals of this Roadmap, through new technologies, new mission concept studies, and competitions for Explorer, Discovery, and Universe Probe missions.

Missions like TPF-I that require precise formation flying of separated spacecraft will demand a serious space engineering effort. Telescopes significantly larger than JWST will demand a very serious investment in lower cost mirror fabrication and in deployment, robotics, or human-aided assembly. For all missions, sensitive detectors must be developed to ensure maximum return on investment in large apertures.

B. Technological Readiness and the Ordering of TPF-C and TPF-I

The 30-year history of proposed searches for other Earths is the history of the debate between advocates of visible coronagraphs and infrared (nulling) interferometers. In the early 1990's coronagraphs were dismissed when it was realized that making a large (>4 m) primary mirror with ~λ/3,000 surface quality was not possible with existing or foreseeable technology. The focus shifted to interferometry and sufficient technical progress was made on infrared nulling that a mid-IR interferometer was presented to the NAS/NRC Decadal review committee for its consideration. However, NASA continued to invest in starlight rejection technologies, "the physics experiments," and mission concept studies at both wavelengths to ensure finding at least one good solution. Starting in 2000, through a competitive peer-reviewed process, NASA utilized the efforts of over 100 scientists and engineers at dozens of universities, NASA Centers, and aerospace companies to survey a very broad range of approaches (59 separate concepts) and finally to arrive at two viable solutions for planet detection: a 3x6 m visible coronagraph and a formation flying interferometer using four 3-4 m telescopes separated by 100-200 m. The latter project was investigated in collaboration with ESA's Darwin project.

With respect to the critical question of starlight rejection, laboratory testbeds of both techniques have shown that rejection to the required level can be achieved either today or with credible extrapolations of existing technology: IR nulling has demonstrated null depths of 10^{-5} to 10^{-6} in reasonable pass bands ($\lambda/\Delta\lambda$<10-100) at 10 μm; at visible wavelengths, the development of highly precise, short-stroke deformable mirrors with 4096 actuators has made it possible to achieve the required output wavefront accuracy (~λ/3,000) and stability (~λ/10,000) using a small deformable mirror to correct a large primary mirror that can be built with conventional techniques to an accuracy of ~λ/100.

With roughly comparable states of readiness for the "physics experiments" needed for starlight rejection at the two wavelengths, the issues in deciding which project, TPF-C or TPF-I, might go first became higher-level system trades. In the case of TPF-C, important issues include setting tolerances of the optical system, vibration control, and the manufacture of the primary mirror. In the case of TPF-I, the issues include formation flying to centimeter-level accuracy, beam transport between spacecraft, the manufacture of 3-4 m cryogenic mirrors, significantly larger than the JWST mirror segments, and testability on the ground. Studies by the TPF project suggested that a coronagraphic mission of limited scope, but still capable of making complete searches for Earths around 35 stars and partial searches of another 120 stars, could be executed more quickly and at a lower cost than an interferometric mission of comparable or greater scope. The natural ordering of the missions appears to be a first reconnaissance and detection of Earths using TPF-C. Subsequently, TPF-I would add mid-IR wavelengths to the visible data obtained with TPF-C, as well as extending the search to more stars, taking advantage of the better angular resolution of the formation-flying system. Thus, in response to the NASA Exploration Vision, the Universe Division elected to proceed with TPF-C, tentatively scheduled for launch in 2014, to be followed by TPF-I, which might be conducted jointly with ESA (and its *Darwin* mission), in the 2015-2020 timeframe, depending on the budgets available at the two agencies.

C. Required Talent

The talent necessary to carry out the missions in this Roadmap currently resides at academic, industrial, and government laboratories throughout the world, and future talent to carry out this program will have to be attracted and developed. The education and public outreach portion of this Roadmap is essential to the future of NASA and to these missions in particular, since the most difficult of them require innovations that we can barely imagine. Experience shows that the extreme challenge of these missions has already attracted top researchers and brilliant students, and will be an excellent way to recruit the next generation of scientists and engineers. Experience also shows that students and researchers respond to the sustained availability of funding. A strong commitment of NASA to a program calls forth the needed talent.

Specific areas of technical expertise required to implement this Roadmap include: mission design, optics, cryogenics, detector physics, low temperature electronics, thermal engineering, and sensing and control systems. Specific areas of required scientific expertise required for planet and planet formation studies include: comparative planetology; paleogeology; star and planet formation processes; interstellar chemistry; astrobiology; astrodynamics and planetary system evolution; atmospheric chemistry, spectroscopy, and evolution; weather and climate; high-pressure solid and liquid-state physics; and laboratory astrophysics. Probing the origins of the conditions for life requires expertise in galactic structure and evolution, the nature of dark matter and energy, stellar structure and evolution, stellar outflows and explosions, interstellar magneto-hydrodynamics, stellar collisions and interactions, and cosmic-ray propagation and effects. In other words, almost every area of planetary sciences and astrophysics is important for full exploration of the two great questions: How did we get here? Are we alone?

D. Required Facilities

At present, the large optics technology needed by these missions is also required by other government agencies, and has been developed primarily in industrial laboratories as a result of competitions. Extremely innovative ideas for large optics are also being developed at optics research universities, and the ground-based community is exploring ways to build 30-m to 100-m telescopes. Significant breakthroughs may come from many directions.

Facilities for testing large optics in vacuum exist at both industrial and government labs. However, each new mission has unique requirements, and each will have its own trade studies to select the most appropriate facilities based on the selected teams and the technical requirements. Temperature, size, and vibration isolation are the most important issues. The largest such facility is NASA's Plum Brook facility, but it is not being used for JWST, partly because of logistics issues, involving the distance and obstacles between the airport and the test chamber, and partly because of the cost to upgrade the facility for optical testing. If Plum Brook is needed for future missions, these problems could be overcome, but at significant cost.

Facilities for detector development are also major investments. Currently astronomical-quality detectors for wavelengths between about 0.3 and 28 micron are primarily available from industrial sources, based largely on semiconductor technology developed for other users. Astronomers typically do acceptance testing because the requirements for dark current and noise are so stringent, and test chambers are so difficult to build at the required performance levels. Vendors that specialize in astronomical detectors are critically dependent on astronomy funding. Detectors for shorter and longer wavelengths are in a very different situation. Astronomy missions are the main customers for the necessary technologies, and consequently NASA is usually the only source of funding for the organizations and facilities that develop them. The recent loss of non-program-specific NASA-wide advanced technology development funding jeopardizes the entire range of UV and far-IR missions in this Roadmap.

E. Unique Requirements

The coronagraph-type missions may require large lightweight monolithic mirrors with surface finish and stability significantly better than is currently available. This issue depends critically on the ability of small deformable mirrors to correct the errors on a sufficiently rapid time scale. Thus, large and very stable structures with active metrology control will be required. The system-level performance of these large structures with picometer metrology can not be fully verified on the ground, so system modeling to predict on-orbit performance will have to advance significantly beyond its current state.

Ultra-precise formation flying of two or more spacecraft with centimeter control is completely new territory. A detailed roadmap for this technology will be needed from the TPF-I project, based on actual flight requirements. Considering the stakes involved, an extensive series of laboratory demonstrations will be needed, ranging from scale models to proof of flight hardware. A decision on the need for a space demonstration of relevant technology will be required when the concept has been further developed.

VI. Critical Inter-Roadmap Dependencies

In the near-term and mid-term, the Search for Earth-Like Planets Roadmap has no architectural dependencies on other strategic roadmaps that would impede its implementation. There are enhancing dependencies with the Transportation and Education roadmaps related to selection of near-term Earth-To-Orbit (ETO) transportation options and effective communication with the public at large. The "Search for Earth-Like Planets" Roadmap has strong programmatic linkage with the "Exploration of the Universe" roadmap (Strategic Roadmap #8) because both roadmaps are to be implemented by the Universe Division of the Science Mission Directorate.

In the far term, alternate observatory architectures would be enabled by enhanced ETO launch capability and deep space nuclear power sources. The Roadmap anticipates telescope apertures that are larger than existing launch vehicle shrouds. JWST will be the first example. The maximum size of stowable aperture segments has a significant influence on the telescope design and aperture deployment or assembly technique. Larger shrouds will enable larger apertures and fewer individual segments – both of which directly affect performance. The ultimate sensitivity of cryogenic infrared observatories could be enhanced substantially if they could be located beyond the main belt asteroids and outside the bulk of our Solar System's cloud of zodiacal particles. Nuclear power for electric propulsion maneuvering and orbit circularization, active cryogenic refrigeration, and operational support would potentially enable this enhanced infrared and submillimeter observatory architecture.

There are synergistic scientific dependencies with a number of other science roadmaps. In general, these dependencies have the character of information transfer. For example, the possible discovery of extra-terrestrial life in our Solar System will influence the interpretation or focus of remote observations of other planetary systems. The absence of life on certain solar planets could expose the possibility of false-positive biosignatures. We may also learn that habitability is strongly influenced by the presence or absence of planetary magnetic shielding and that water, alone, is insufficient for life.

There are no identified dependencies related to the International Space Station and no expectation to establish a lunar-based observatory as part of the Roadmap plan.

Identified Strategic Roadmap dependencies are listed in Table VI-1. This table summarizes significant external relationships between this Roadmap (SR-4) and other Strategic Roadmaps. Following the guidelines of the relational database, events between roadmaps are characterized as *dependent* (exclusively), *enabling* (necessary, but not sufficient), *enhancing* (beneficial, but not critical), or *synergistic* (of mutual benefit). Arrows point toward the roadmap which accrues the benefits from the event dependency; arrow colors indicate the status of linkage resolution (*red*=fundamental disagreement, *yellow*=resolution process pending, *green* = event compatibility achieved for both roadmap committees. Specific technology dependencies and linkages of the missions roadmapped in this report are detailed in Chapter V above.

Key Dependency	Linked Roadmap			Nature of Relationship and Status	SR-4 Roadmap Event	Time-frame
	Name		Event			
Expanded launch vehicle shroud size, capability	SR-5	Transportation	New or improved ETO capability	Enhancing ⇨	Observatory architecture designs	Far
Science and programmatic linkage - understand joint capabilities	SR-8	Universe	Detection of extrasolar planets and evidence of biologic activity	⇦ Synergistic ⇨	Discoveries related to origin, evolution, and structure of the Universe	Near, Mid, Far
Expansion of biosignatures	SR-2	Mars	Develop Mars science strategy	⇦ Synergistic ⇨	Investigations or discoveries of biosignatures	Mid
Expansion of Habitable Zones (Icy Moons)	SR-3	Solar System	Knowledge of range of habitable conditions on Jupiter icy moons	⇦ Synergistic ⇨	Special Habitable Locations	Mid
Mission requirements influence transportation design	SR-5	Transportation	Transportation architecture designs	⇦ Enhancing	Identify future transportation requirements	Near
Understanding Earth as example of terrestrial planet	SR-9	Earth Science	Enhanced understanding of biomarkers	⇦ Synergistic ⇨	Enhanced understanding of biomarkers	Near, Mid
Habitability; planet star connection	SR-10	Sun-Earth	Magnetosphere	⇦ Synergistic ⇨	Role of planetary magnetic fields	Near, Mid
Public interest and support	SR-12	Educate	Public outreach, engagement	Enabling ⇨	Mission advocacy, Science Discoveries	Near, Mid, Far
3 AU IR Observatory deployments; telescopes far from Earth	SR-13	Nuclear	Deep space power generation, nuclear-electric propulsion	Enhancing ⇨	Observatory architecture designs	Far

Table VI-1. Inter-roadmap dependencies between SR-4 and the other Strategic roadmaps.

Capability Roadmap Dependencies

Suggested Capability Roadmap dependencies are listed in Table VI-2. This table summarizes the proposed relationships between this Roadmap (SR-4) and the various capability roadmaps. The SR-4 Roadmap committee has held discussions with CR-4 (Advanced Telescopes and Observatories) and CR-12 (Scientific Sensors and Instruments) and generally accepts the proposed capability needs from these roadmaps. The proposed products from other capability areas are not sufficiently well defined by database information to be immediately accepted. Additional information is required.

SR-4 expects that system level test and verification of future very large space optical systems will be difficult, if not impossible, on the ground or in low-Earth orbit. The adverse effects of gravitational loading, terrestrial environments, LEO thermal instability, and physical size are the sources of these testing issues. Advanced precision modeling and simulation tools and materials properties data will be required to stitch complex subsystem verification data together to achieve system level confidence. These tools should be a product of CR-14. Capabilities related to exploitation of the moon as a site for planet search observatories are not required. There is no expectation of a lunar observatory in the planet search roadmap.

Key Dependency	Linked Roadmap: Name		Linked Roadmap: Event	Nature of Relationship	SR-4 Roadmap Event and Status	Time-frame
Precision Low-Thrust	CR-3	In-Space Transport.		Enabling	Observatory Design	Mid, Far
Micro-Newton thrusters				Enabling	Observatory Design	Near, Mid
Control of flexible structures	CR-4	Advanced Telescopes and Observatories		Enabling	Observatory Design	Near, Mid
Interferometer systems				Enabling	Observatory Design	Near, Mid
Algorithms and sensors for formation-flying				Enabling	Observatory Design	Near, Mid
Wavefront sensing and control				Enabling	Observatory Design	Near, Mid
Large lightweight optics				Enabling	Observatory Design	Near, Mid, Far
Rendezvous and docking	CR-10	Autonomous Systems and Robotics		Enhancing	Observatory Design	Mid, Far
Repair and servicing				Enhancing	Observatory Design	Mid, Far
Deployments				Enhancing	Observatory Design	Mid, Far
Operations planning and scheduling				Enhancing	Observatory Design	Near, Mid, Far
Detector technologies and performance	CR-12	Scientific Instruments and Sensors	Improved performance of science detectors	Enhancing	Sensitivity estimates to support observatory designs	Near, Mid
Cameras, detectors, spectrometers				Enabling	Observatory Design	Mid, Far
Cooling				Enabling	Observatory Design	Mid, Far
System modeling tools	CR-14	Advanced Modeling, Simulation, Analysis	Tools for system modeling and verification	Enabling	Observatory Designs, Test and Verification	Near, Mid
Science / engineering data processing and fusion				Enhancing	Science Extraction	Near, Mid, Far
Complex systems integration and test	CR-15	Systems Engineering Cost/Risk Analysis		Enhancing	Observatory Design	
Ensure outcome or optimize performance within constraints				Enhancing	Observatory Design	

Table VI-2. Inter-roadmap dependencies between SR-4 and the Capability roadmaps.

Appendix 1: National Policy Framework and External Constituencies

The Search for Earth-like Planets was highlighted in *A Renewed Spirit of Discovery –The President's Vision for U.S. Space Exploration,* and reiterated as a key NASA objective in the Space Exploration Vision articulated in the *President's Commission on Implementation of United States Space Exploration Policy* (the "Aldridge Report"). That report called for "advanced telescope searches for Earth-like planets and habitable environments around other stars" as one of the foundations of its exploration goals. In fact, all recent NASA planning documents have included as one central strategic goal to "conduct advanced telescope searches for Earth-like planets." The NASA Vision Statement includes the charge "**To find life beyond**." The NASA Mission Statement expressly challenges us "To explore the Universe and **Search for Life**." The National Academy of Sciences Decadal Survey: *Astronomy and Astrophysics in the New Millennium* endorsed the search for and characterization of Earth-like planets as an exciting frontier for space astronomy in the coming decade. The *Origins 2003* Roadmap, the *NASA Astrobiology Roadmap 2003*, and the 2003 Strategic Plan of the former Space Science Directorate each had as centerpieces the discovery and exploration of planets, habitable environments, and signatures of life outside the Solar System.

Strategic Roadmap #4, "**The Search for Earth-like Planets,**" builds on a strong legacy of scientific advances and policy heritage and represents NASA's *only* plan for realizing these exploration goals.

External constituencies for this Strategic Roadmap include the aerospace industry, astronomical researchers in academia, planetary scientists, the ground-based astronomical community interested in large telescopes, astrobiology researchers, K-12 schools, the NRO, DOD, OMB, and Congress. For instance, NASA is partnering with the DOD, NSA, and NRO in pursuing large, advanced space optics for the purpose of furthering the state of the art in lightweight mirror fabrication and space assembly. International constituencies include ESA, the Canadian Space Agency, and JAXA.

Appendix 2: Bringing the Universe down to Earth: Education and Public Outreach (EPO)

The discovery of Earth-like planets that may host life is a stunning prospect for people of all ages and cultures. The subject and its lexicon is broadly accessible to the uninitiated. The first confirmed Earth-like planets around another star will fundamentally alter our place in the cosmos, with implications as profound as the work of Copernicus, Kepler, and Galileo. This decades-long endeavor has the potential to ignite public excitement and stimulate the public imagination akin to the greatest discoveries in the history of culture.

Unique Education and Public Engagement Opportunities

The missions and programs that support the telescopic search for Earth-like planets and habitable environments around other stars present distinct opportunities to advance NASA's Strategic Objective # 13:

> *Use NASA Missions and other activities to inspire and motivate the Nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the Nation.*

This lofty goal serves down-to-Earth needs. We must generate and sustain an ample workforce of scientists and engineers—some of those who will implement the missions in this Roadmap are now only in elementary school. A strong education program provides 1) a necessary return on the public's investment in science exploration; 2) develops pathways for students to enter the fields of science, technology, engineering, and mathematics (STEM) careers, and 3) stimulates the public appetite for NASA Missions. Beyond the STEM careers themselves, the broader public must achieve a basic level of scientific literacy. This is not only good for the Nation and our democracy, but it may well be a prerequisite for the support that a multi-decadal program of exploration and discovery requires. The final report of the Moon-to-Mars Commission identified sustaining public interest as possibly the single greatest challenge facing NASA's overall Space Vision.

Public Engagement: Sharing Exploration and Discovery

NASA will need to plan proactively for the worldwide interest that the discovery of Earth-like worlds will cause. The quest has the potential to enter the mainstream of popular culture, capturing the public imagination at levels unmatched since the height of the Apollo program. Yet, the 30-year research timeline and attendant capital investment requires sustained public support. Unlike Apollo, this will be a journey, not a race. To support this major effort, the public needs to be emotionally engaged in the excitement of the Missions, and to be rationally informed about the goals and accomplishments along the way. This may require new and novel approaches to public engagement, as science and engineering compete for public attention, in addition to the traditional formal and informal education programs that serve complementary goals.

Public engagement builds grass-roots support that can sustain the search for Earth-like planets and habitable environments. Examples of how this has worked in the past include SETI@home, the distributed computing phenomenon initiated by UC Berkeley, and the many billions of hits received on the Mars Rover web site. Both cases demonstrate a burning desire of the public to be authentically involved in the search for life beyond Earth. Strategies that allow members of the public to participate in the discovery of Earth-like planets have the potential to generate national and international support for the Missions and programs, and such opportunities should be fundamentally linked to the Mission requirements where possible.

Public engagement encompasses the media, individual participation, and events. Examples include:

- Multi-media products for home, at school, and in public spaces like planetaria engage the public in NASA's discoveries
- Kiosks in public spaces like libraries, national parks, and shopping malls that interactively provide current news
- Volunteer networks such Solar System Ambassadors and the Night Sky Network that enable trained individuals to reach broad public audiences on NASA's behalf
- National and local events that highlight missions, such as the Year of the Telescope in 2009
- Mission launches that are strategically broadcast live via science centers and museums
- Websites like the PlanetQuest that offer engaging interactives and story-telling visualizations that carry the story to ever larger audiences.
- Electronic, broadcast and print media that carry news of the discoveries
- Online gaming communities that build new planetary systems inhabited by creatures of the imagination that interact sending parties of exploration, invasion, and colonization.
- Individuals modeling of planetary systems, and habitable worlds on home computers
- Yet-to-be-invented interactive experiences that will allow people to explore NASA data via the National Virtual Observatory (NVO) or the future sensor net.
- New cultural phenomena, such as blogging.

Public interest in astronomy, space science, and NASA is often fed by local science centers and museums, where exhibits, planetarium programming and IMAX films explain the process of science and share the thrill of exploration and discovery. These institutions offer opportunities of high leverage for NASA to communicate with the public. Their innovative programming and exhibits make them significant partners in public engagement, especially when the content is disseminated to other, smaller communities.

Education: NASA Science in the Classroom:

> "Everyone involved in exploring space today can make a difference for tomorrow by using the excitement of space exploration to engage the broadest possible cross section of America's children in learning math, science, and engineering." *Report of the President's Commission on Implementation of United States Space Exploration Policy,* p. 42

Exploration, discovery, and understanding are communicated to teachers and students via formal curriculum, instruction, and experiential learning. A coherent program for education will thread through the successive missions, sharing legacy resources and developing new products, partnerships, and strategies as national education goals and communications technologies evolve.

Education programs that will leverage NASA's investment by focusing on professional development for educators who support public science literacy include:

- K-12 teachers, especially STEM teachers,
- informal educators at science centers and planetariums,
- undergraduate faculty who instruct the "science for citizens" general education courses in astronomy, astrobiology, geology, geobiology, etc.

The goal of such programs will be to enrich the talents of educators, who in turn inspire students to support the scientific enterprise and/or pursue studies that lead to STEM careers. Community colleges and institutions that serve historically underrepresented groups are important partners, since most K-12 teachers take their STEM coursework at these institutions. The NASA Center for Astronomy Education professional development workshops now serve these faculties with great success.

> "The Commission finds that the space exploration vision offers an extraordinary opportunity to stimulate mathematics, science, and engineering excellence for America's students and teachers—and to engage the public in a journey that will shape the course of human destiny." *President's Commission on Implementation of United States Space Exploration Policy: A Journey to Inspire, Innovate, and Discover*, p. 41.

As college-age students prepare to join the NASA workforce, their education will necessarily require both breadth and depth in the classroom as well as laboratory and hands-on experiences with NASA missions and programs. The integration of many disciplines is required to explore Earth-like worlds and habitable environments; this points to a need for cross-trained teams of scientists, technologists, and engineers. The planet-finding missions utilize a variety of space-based and ground-based telescopes, as well as a rich program of research and analysis, laboratory astrophysics, and theoretical investigations supported by Research and Analysis (R&A). This is a diverse environment in which to train the STEM workforce who will actually conduct missions in the future. Programs of scholarships, fellowships, and training for undergraduate, graduate, and post-doctoral scientists and engineers should be supported via academic and research institutions, NASA centers, and in industry. Programs could include:

- National Research Council Fellows
- TPF Foundation Science program
- Michelson Science Fellowships
- NASA Astrobiology Institute Internships and Fellowships
- NASA's proposed university-based Virtual Space Academy
- Programs similar to NSF's Research Experiences for Undergraduates and Research Experiences for Teachers

Core EPO Values and Principles

To create quality education and public outreach, NASA programs share core values: 1) coherence to meet varied audience needs; 2) coordination with other NASA initiatives, 3) leverage via national and international partnerships; 4) scientific and technical participation by the NASA team; 5) hands-on experiences involving real research and data; and 6) engaging diverse people with NASA and in the NASA workforce. To achieve excellence, EPO programs require: dedicated resources (~2% of a mission's or program's total cost), comprehensive planning, implementation of EPO requirements in the design and development of missions, alignment with broader Agency efforts, and reliable assessments of the effectiveness of all EPO activities. Together, public engagement and education and outreach programs can reach the broadest audiences to achieve NASA's strategic objectives.

Appendix 3: External Partnerships: Engaging the Nation and the World

In the last ten years we have discovered over 150 extrasolar planets, the existence of water on Mars, and the possibility of water below the crusts of Jupiter's moons Europa and Ganymede. We have discovered complex connections between Earth's atmosphere, oceans, and continents that drive Earth's weather and make it habitable for highly diversified forms of life. We have quantified the Sun's decadal variability and its influence on Earth's biological, chemical, and physical processes. Public interest in the exploration of our Solar System and beyond is very high, but is tempered by cost and feasibility concerns. Maintaining the momentum of discovery and keeping the exploration initiative on a viable and productive path will require a global effort of partnerships among USG agencies, US industry, and international partners (both government and industry). This partnership of discovery will fuel economic, social, and intellectual growth worldwide and foster technical development at a faster rate than NASA might accomplish on its own.

A. A Balanced Program between NASA, Academia, and Industry

The first step in laying out a roadmap is to set the vision. The US Space Exploration Vision provides the overarching context for the Nation's and NASA's plans for future space missions. The fundamental scientific questions and required technological innovations are defined by academia and industry, and these in turn enable the goals and objectives of this Vision. Answering the fundamental science questions through a series of targeted missions to explore these questions is NASA's mission. Garnering and sustaining support for these missions will be difficult if there are visible space program failures. There have been a series of special reports in the last few years (e.g., the Young Panel, the CAIB report) that not only focused on hardware failures that resulted in loss of a mission, but on failures of program management that resulted in program plans that were overly ambitious and unrealistic from the beginning, resulting in significant cost and schedule overruns. Industry's role is to work in partnership with NASA and the science community to create a realistic program within the cost and schedule boundaries dictated by NASA's budget. To do this requires that all three work in concert from the outset to establish a comprehensive systems engineering approach that balances the program's parameters, costs, schedule, and science requirements simultaneously and that efficiently addresses the risks and trade-offs. To maximize our investments we will need simple, elegant solutions that progressively build on previous technology, while never sacrificing safety. Successful program planning and execution requires proactive management of such complex projects. This necessitates an active dialogue throughout program planning, development, and operational phases that constantly factors in the evolving scientific requirements, enabling technologies, and engineering practices. Such a dialogue will result in realistic scientific goals consistent with the state of the requisite technologies and, hence, in realistic cost, schedule, and risk plans. Re-engineering programs like SIM when they are years into development is otherwise an inefficient and costly use of resources. Industry can play a stronger role in the formulation of programs by being an equal partner early in concept formulation and definition.

B. The Importance of Competition

Competition is a fundamental tool in soliciting a broad spectrum of ideas for mission implementation. Competition has a multitude of dimensions in this context:

1) There is the competition between PIs who propose innovative missions, thus affording NASA the broadest set of options to further its scientific goals. Similarly, there is the competition of ideas for strategic missions, too large for PIs, which are presented to NASA committees and reviewed by NAS committees.

2) There is the competition among contractors to become NASA's industrial partners in selected missions. Industry will often match investments made by NASA in pre-Phase A and Phase A studies, providing NASA with a broad range of technical and programmatic ideas for implementing these missions. During Phase C/D proposals, competition can be used judiciously to explore options for balanced technical development and risk reduction, within budget and schedule margins. If this is not done, contractors are unduly encouraged to make overly optimistic assumptions in order to be competitive. As a result, safety and program realism suffer. The recommendations of the Young Panel should be reviewed before any RFP is written for an ambitious new program.

and

3) There is the competition between NASA and its international counterparts, such as ESA, the Canadian Space Agency, JAXA, and the Chinese space agency. Such competition promotes a global debate on where humankind should focus its space exploration resources. Often ESA and NASA have similar mission goals and in the interest of leveraging resources will decide to collaborate, rather than compete. However, early competition creates a plethora of ideas, from which partners can later choose the best set of options and define their respective roles and responsibilities. The technical and resource challenges of a program like TPF-I will require employing all aspects of the above. Engagement between NASA, industry, academia, and international partners cannot begin early enough.

C. USG agencies

NASA has a history of working effectively with other agencies, which will be essential to achieve its Exploration vision and in the search for Earth-like planets. The NSF is NASA's partner in furthering American science and technology and should work with it to promote an expanded view of Earth and Space science. For example, the NSF is partnering with a European consortium to build the Atacama Large Millimeter Array (ALMA) to study the formation of solar systems around very young stars in relatively nearby dark clouds. The NSF is also the largest single partner in the GEMINI 8-meter optical / IR telescopes, and GEMINI is now making significant investments in detecting extrasolar planets. These new investments include developing an extreme adaptive optics system to image extrasolar Jupiter-like planets orbiting nearby young stars and an infrared spectrograph which will be optimized to detect Earth-mass planets in the solar neighborhood. The NSF is also investing in visible-light ground-based radial-velocity studies that are identifying ever lower-mass extrasolar planets around nearby Sun-like stars.

NASA should also strengthen its ties to other agencies. For instance, it is formulating a long-term plan with NOAA to gather environmental data through joint missions that also can provide operational forecasting capability for NOAA and Earth science data for NSA. Similarly, NASA needs to build strong ties to DOE, DOD, DARPA, and the NRO to multiply the return on the Nation's investment in fundamental sensor, mirror fabrication, optics, space assembly, and propulsion technologies that will be crucial to executing the extrasolar planet discovery missions of this Roadmap. In this vein, NASA is coordinating technology efforts in large advanced space optics through the Large Optics Working Group of the Space Technology Alliance, an affiliation of the Federal Space-Faring Agencies. Specifically, collaborations are being pursued in lightweight, rapid, and low-cost mirror fabrication.

D. Importance of International Collaboration

NASA has a long and successful history of collaboration with the space and research agencies of other nations. In fact, almost all of NASA's Earth observation missions include substantial international participation. The Global Earth Observation System of Systems (GEOSS) includes over 60 nations and more than 40 international research and environmental forecasting organizations. Likewise in space science, ESA and CSA participation in JWST is a fundamental part of the cost strategy of that program. ESA is providing the Ariane launch vehicle and the Near-InfraRed Spectrograph (NIRSpec) instrument, with NASA providing the detectors and microshutters. ESA is also organizing a European partnership to produce the opto-mechanical assembly of the Mid-Infra-Red Instrument (MIRI). The whole MIRI effort is a 50-50 partnership with ESA, with NASA/JPL assuming project leadership and the US providing the science team lead. The Canadian Space Agency is also a partner and provides the Fine Guidance Sensor. ESA and CSA are to get guaranteed allocations of observing time of 15% and 5%, respectively.

Two other missions, which are important to this Roadmap and which are currently in development, have significant international participation. The *Herschel* mission is led by ESA, with 20% participation from NASA. The US provides *Herschel* with advanced detectors and coolers, which have helped advance these technologies in the US. SOFIA is led by NASA with a 20% contribution from the German Aerospace Center (DLR) in the form of the SOFIA telescope and a portion of the SOFIA operating needs. Both of these missions will be very important for the planet formation and habitability science objectives of this Roadmap.

The search for Earth-like planets will require continued international participation and cooperation to leverage resources, share scientific data and responsibilities, and promote continued funding by the various government agencies involved in the emerging scientific field of planetary exploration outside the Solar System. This is particularly true with regards to TPF-I and NASA has begun discussions with the ESA/Darwin project. Likewise, industry is becoming more and more global and is partnering across borders to provide the best overall technical and cost solution to its customers. America will benefit from more international scientific and technical cooperation.

Appendix 4. Synopsis of Missions to Explore Extrasolar Planets

The rich science program described in this Roadmap draws upon a vast array of activities including ground- and space-based observations, data analysis, theory, and modeling. The sources of observations include ground observatories, balloon and sounding rockets, small and medium size competed missions, and the major strategic missions. This appendix of the Roadmap summarizes the core and strategic missions that are called for to implement this exploration vision. First, Figures A4-1 ("Exoplanet Detection and Characterization") and A4-2 ("Formation & Evolution of Exo-Planetary Systems from Disks") lay out the general time sequence of the missions for the two major scientific themes and identify key relations and products. Then, each mission is described in turn and its unique role in this Roadmap is summarized.

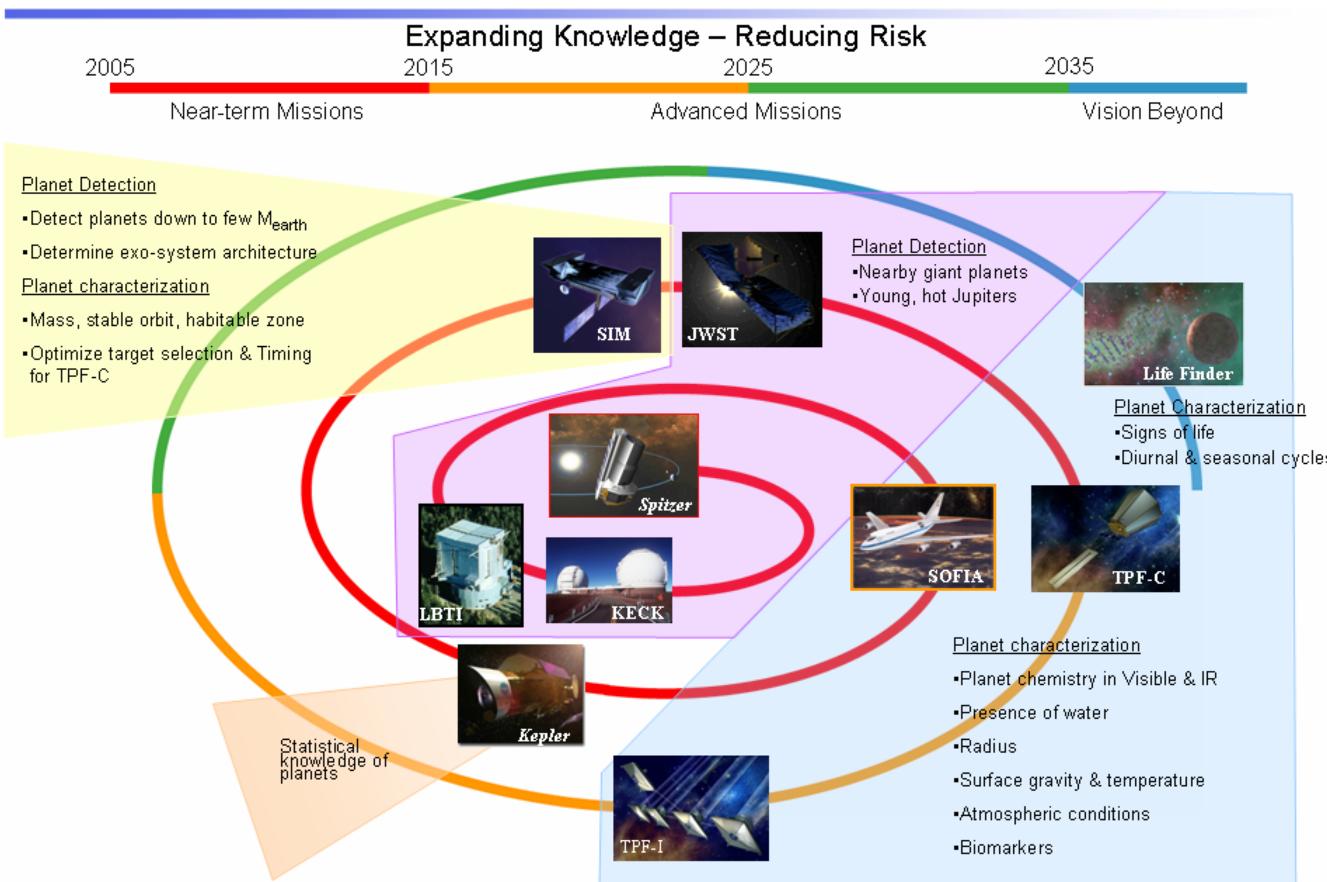


Figure A4-1. Key products and relationships of recommended missions that focus on exoplanet detection and characterization. Colors indicate launch decade as indicated at the top.

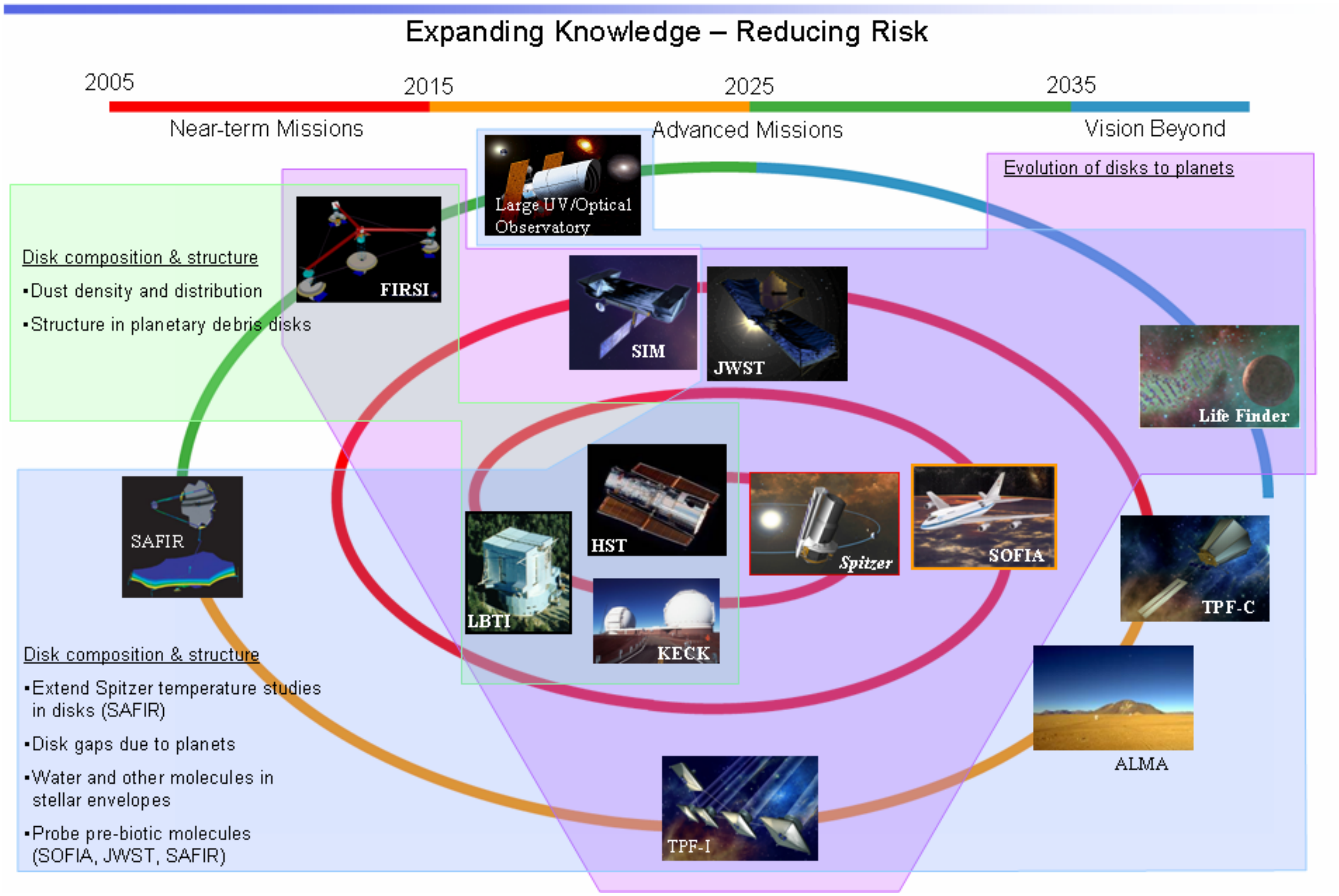


Figure A4-2. Key products and relationships of recommended missions that focus on planet formation and evolution. Colors indicate launch decade as indicated at the top.

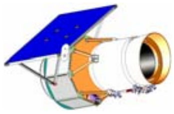
Missions for 2005 – 2015

NASA supports a broad science program in conjunction with the W.M. Keck Observatory in Hawaii. This program has two main thrust areas: first the sponsorship of community-accessible time on single Keck telescopes to pursue Roadmap science goals; and second, the development and operations of the **Keck Interferometer (KI)**. The single-Keck program has been in place since 1996, and has been extremely successful in producing important scientific results such as radial velocity exo-planet detections, spectral characterizations of L and T dwarfs, and mid-infrared imaging of planetary debris disks. KI has combined the infrared light collected by the two 10-meter Keck telescopes to undertake a variety of astrophysical investigations. Among the issues addressed by KI will be the location and amount of zodiacal dust in other planetary systems and, possibly, the astrometric detection and characterization of exo-planetary systems around stars in the solar neighborhood. This first in-depth and long-term census of planets will be an important contribution to our understanding of the architecture and evolution of planetary systems, and will be key in helping to define the requirements and the architecture for TPF.

The **Large Binocular Telescope Interferometer (LBTI)** will further a variety of Roadmap goals in star and planet formation through both nulling and wide-field imaging interferometry. Primary among these goals is a planned systematic survey of nearby stars to understand the prevalence of zodiacal dust and gas giant planets and to determine a system's suitability for terrestrial planets. The modest baseline and common mount design of the dual 8.4-meter LBTI allows uniquely sensitive infrared observations of candidate planetary systems through nulling interferometry. The development of nulling technology and observing techniques will help create a mature technological basis for a TPF mission. The LBTI also allows wide-field, high-resolution imaging of objects down to brightness levels similar to filled aperture telescopes.

The **Stratospheric Observatory for Infrared Astronomy (SOFIA)** will study sites of star formation, formation of new solar systems, survey the debris disks which are planet-forming regions, and study Neptune-sized and larger extrasolar planets through the transit technique. In addition, SOFIA will conduct a number of other astrophysics investigations such as observations of the cold interstellar medium, and the center of our galaxy at high spatial resolution at far-infrared wavelengths. It is a joint U.S. (80%) and German (20%) observatory that consists of a 747 aircraft with a telescope as large as HST (2.5m). SOFIA will also function as a unique platform for developing, testing, and reducing risk of new IR instrument technologies, particularly detectors for future missions such as SAFIR. It will have a prominent education and public outreach program, including involving high school teachers and students in its flights and observations. SOFIA will be making observations in 2006.

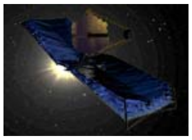
Kepler is a Discovery Program mission scheduled for launch in 2008. This provides an excellent example of the kind of moderate scale missions that can contribute to the Roadmap in important ways. The *Kepler* mission is specifically designed to photometrically survey the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone and provide fundamental progress in our understanding of planetary systems. The results will yield a broad understanding of planetary formation, the frequency of formation, the structure of individual planetary systems, and the generic characteristics of stars with terrestrial planets. These results will be instrumental in determining how deep TPF will have to look to find an adequate sample of planetary systems to find and characterize habitable planets. *Kepler* is a simple 0.95-m Schmidt telescope, with a very challenging detector array consisting of 42 CCDs, each with 2200 x 1024 pixels.



WISE. WISE (Wide-field Infrared Survey Explorer) is a MIDEX class explorer mission to conduct an all-sky survey from 3.3 to 24 microns up to 1000 times more sensitive than the IRAS survey. Among other things, WISE will measure the local mass function of brown dwarfs down to a few Jupiter masses. WISE has a 40-cm telescope and reimaging optics, giving 6" FHWM resolution. It consists of a single instrument with HgCdTe and Si:As arrays at 3.5, 4.6, 12 and 23 microns. WISE is scheduled for launch in 2009 aboard a Delta rocket.

The **Space Interferometry Mission (SIM): PlanetQuest** will be the first observatory capable of detecting and measuring the mass of planetary bodies with a few times the mass of Earth in orbit around nearby stars. SIM PlanetQuest will take a major step forward in answering some of the defining questions in our exploration of the Universe: “Are we alone?” Are there other worlds like our own home planet, existing within planetary systems like our own Solar System? SIM will extend mankind’s exploration of nearby planetary systems into the range of the rocky, terrestrial planets for the first time, permitting scientists to refine their theories of the formation and evolution of planets like Earth. This census will form the core of the observing programs for subsequent missions that will investigate in detail the nature of these newly discovered worlds. SIM will aid in defining the early “target list” for TPF by identifying systems to focus on, i.e. those with candidate planets of a few Earth masses or a dynamical void that would imply the presence of such planets, as well as those systems to avoid, i.e. systems with gas or ice giants near the habitable zone. Orbital information from SIM could help in detailed planning of TPF observations. SIM will provide for the first time the properties of planetary systems in orbit about young stars where imaging is limited by photospheric activity and rapid rotation, helping to answer questions about the formation of systems of these systems. SIM will provide all-important data on planetary masses, which when coupled with data from TPF-C/I will yield densities and surface gravities crucial to complete physical characterization. In addition to its scientific goals, SIM will develop key technologies that will be necessary for future missions, including precision location of optical elements to a fraction of the diameter of a hydrogen atom (picometers) and the precise, active control of optical pathlengths to less than a thousandth the diameter of a human hair.

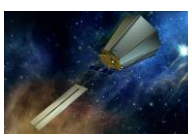
Beyond the detection of planets, SIM’s extraordinary astrometric capabilities will permit determination of accurate positions throughout the Milky Way Galaxy. This will permit studies of the dynamics and evolution of stars and star clusters in our galaxy in order to better understand how our galaxy was formed and how it will evolve. Accurate knowledge of stellar positions within our own galaxy will allow us to calibrate luminosities of important stars and cosmological distance indicators enabling us to improve our understanding of stellar processes and to measure precise distances throughout the Universe.



***James Webb* Space Telescope (JWST)** will have an aperture 2.7 times that of HST and about an order of magnitude more light-gathering capability. Because the prime science goals for JWST are to observe the formation and early evolution of galaxies, JWST's greatest sensitivity will be at mid- and near-infrared wavelengths, where the expansion of the Universe causes the light from very young galaxies to appear most prominently. JWST will be a powerful general-purpose observatory capable of undertaking important scientific investigations into a very wide range of astronomical questions, including those that are central to the Roadmap themes. JWST will be a powerful tool in the exploration of extrasolar planetary systems by studying planet forming regions, dust disks and their dynamics, birth of stars and formation of early systems, and studying how the chemistry that can lead to life is delivered to planetary systems.

The telescope diameter of JWST will be 6.5 meters and JWST will be celestial background-limited between 0.6 and 10 microns, with imaging and spectroscopic instruments that will cover this entire wavelength regime. JWST has a requirement to be diffraction-limited at 2 microns. With these capabilities, JWST will be a particularly powerful tool for investigating fundamental processes of stellar formation and early evolution, as well as the later stages of evolution. In both cases, dust almost completely blocks our ability to observe the light from rapidly evolving stars, so that detailed observations have to be carried out at longer wavelengths.

The European Space Agency and the Canadian Space Agency have agreed to contribute significantly to the JWST project. These contributions will be important in significantly enhancing the overall capabilities of the observatory.



The **Terrestrial Planet Finder Coronagraph** (TPF-C) will directly detect and study planets outside our Solar System from their formation and development in disks of dust and gas around newly forming stars to their evolution and even potential suitability as an abode for life. By combining the high sensitivity of space telescopes with revolutionary imaging technologies, TPF will measure the size, temperature, and placement of terrestrial planets as small as Earth in the habitable zones of distant solar systems as well as their gas giant companions. In addition, TPF spectroscopic capability will allow atmospheric chemists and biologists to use the relative amounts of gases like carbon dioxide, water vapor, ozone and methane to find whether a planet someday could or even now does support life. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, including gas giants, terrestrial planets and debris disks. TPF's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new solar systems is an important scientific motivation for the mission. However, TPF's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an Earth orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest.

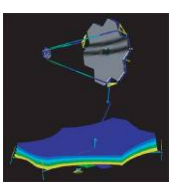
The visible-light coronagraph will use a single telescope with an effective diameter near

8 meters, operating at room temperature, and required to achieve a billion-to-one image contrast in order to isolate the signal from a planet from that of the star. Very precise, stable control of the telescope optical quality will be required. TPF-C has carried out an extensive program of technology development along multiple paths to enable this unprecedented capability, and has now demonstrated in laboratory conditions the ability to produce contrasts in the required regime. TPF-C is targeted for launch in 2014.

Missions for 2015 – 2025

The **TPF-Interferometer** (TPF-I) will be a long-baseline interferometer operating in the infrared. TPF-I will use multiple (≈4), 3–4-meter-diameter telescopes configured as an array operated on separated spacecraft over distances of a few hundred meters. The telescopes will operate at extremely low temperatures of ≈40 kelvin, and the observatory will necessarily be large. However, the image contrast requirement, “only” a million to one, and thus the required system optical quality, will be less challenging at infrared wavelengths than the TPF-C challenge of 1 billion to one at visible wavelengths.

The European Space Agency (ESA) has been actively studying an infrared interferometer with essentially the same science goals as TPF, referred to as Darwin. Under a NASA/ESA Letter of Agreement, scientists and technologists in both agencies are discussing ways in which the preliminary architecture studies can lead to effective collaboration on a joint mission.



The **Single Aperture Far-InfraRed** mission, consisting of a single 8–10-meter telescope and operating in the far infrared, will serve as a building block for the Life Finder while carrying out a broad range of scientific programs beyond JWST and *Spitzer*. These include probing the epoch of energetic star formation in the redshift range $1<z<10$ at a wavelength regime that can easily detect continuum and cooling-line emission from dust-enshrouded primeval galaxies with an angular resolution capable of isolating individual objects at or below the limits of the Hubble Deep Field; investigating the physical processes that control the collapse and fragmentation of molecular clouds to produce stars of various masses by mapping of cold, dense cores at <100 AU resolution at the peak of their dust emission and using gas phase tracers such as H_2, H_2O, CO, [OI], [NII]; learning about the era of cometary bombardment that may have determined the early habitability of Earth by making high spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars; and studying the nature of the recently discovered objects in the Kuiper Belt of our own Solar System which may be remnants of our own planet formation process.

Universe Probes: By the middle of the next decade, NASA will be in a position to call for a series of mid-scale missions with competed science that contribute in important ways to the overall exploration of extrasolar planetary systems.

Missions for 2025 – 2035

Two missions still far in the future because of their demanding technologies have strong relevance to Roadmap goals. The first is the **Life Finder**, which would provide high-resolution spectroscopy on habitable planets identified by TPF. This information would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth. Achieving that goal will require observations beyond those possible with TPF. For example, searching the atmospheres of distant planets for unambiguous tracers of life such as methane (in terrestrial concentrations) and nitrous oxide would require a spectral resolution of ~1,000, utilizing a version of TPF with 25-meter telescopes.

Finally, in the search for exo-solar planets capable of harboring life, a mission for the far future that will serve to challenge our imaginations and our technological inventiveness, is **Planet Imager**. Perhaps using a formation of a dozen ten-meter telescopes, this mission may some day return images our children or theirs could use to study the geography of a pale blue planet orbiting a star similar to ours across the gulf of space, time and imagination. While no clear path to accomplishing this mission currently exists, its appeal is so great that it will remain a distant vision on our Roadmap until future generations make the dream a reality.

Appendix 5: Bibliography of Key Agency and NRC Documents

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Appendix 6: Acronyms and Mission List

ALMA Atacama Large Millimeter Array
COROT COnvection ROtation and planetary Transits
FIRSI Far-Infrared and Submillimeter Interferometer
Herschel
HST *Hubble* Space Telescope
JWST *James Webb* Space Telescope
Keck-I *Keck* Interferometer
Kepler
LBTI Large Binocular Telescope Interferometer
Life Finder
LUVO Large UV/optical Observatory
MIRI Mid-Infra-Red Instrument
NIRSpec Near-InfraRed Spectrograph
NVO National Virtual Observatory
Universe Probes
Planet Imager
PTI Palomar Testbed Interferometer
SAFIR Single Aperture Far-InfraRed mission
SIM Space Interferometry Mission - PlanetQuest
SOFIA Stratospheric Observatory for Infrared Astronomy
Spitzer
TPF Terrestrial Planet Finder
TPF-C Terrestrial Planet Finder Coronagraph
TPF-I Terrestrial Planet Finder Interferometer
VLTI Very Large Telescope Interferometer
WISE Wide-field Infrared Survey Explorer
XMM-Newton

Appendix 7: Strategic Roadmap team, Search for Earth-like Planets

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