## 1. Executive Summary

The goals of the Navigator Program at NASA are to find Earth-like planets around nearby stars, to determine if they are habitable, and to search for signs of life. Three strategic missions are planned to carry out this program: the Space Interferometer Mission Planetquest (SIM), the Terrestrial Planet Finder Coronagraph (TPF-C), and the Terrestrial Planet Finder Interferometer (TPF-I). These missions, along with the PI-class Kepler project, will each discover unique new knowledge about extrasolar planets, synergistically building on the other missions. This letter outlines the scientific contributions of these missions, and the scientific synergies among them. We show that the scientific results from SIM are vital to maximize the return from TPF-C and TPF-I.

## 2. Introduction

Over 155 extrasolar planets have been discovered since 1996. These planets were detected using Doppler spectroscopy instruments that are sensitive to large, massive objects like our Solar System's giant planets. Other types of instruments will be needed to detect small, light objects like Venus, Earth, and Mars, local examples of "terrestrial planets". NASA and the US astronomy community currently plan to fly four distinct missions to search for terrestrial planets. This set of missions is designed to return maximum scientific benefit, and in particular to tell us, beyond reasonable doubt, if nearby planets can be found that are habitable and show signs of life.

For maximum scientific impact, each mission should be launched as soon as it is technologically ready. The scientific impact will be reduced substantially if fewer missions are launched.

## 3. Missions to Detect and Characterize Extrasolar Planets

**3.1 Kepler** will detect planets indirectly by measuring the dimming of a star when a planet crosses in front of the stellar disk. Kepler will tell us the size of the planet, how close it is to the star, and the length of its year, using the measured depth, duration, and repeatability of dimming. It will do this with a single small telescope, staring at a distant field of stars (not nearby stars) for several years. Kepler will be most sensitive to any large-diameter planet that is close to its star, a key to telling us about planet formation and migration. Since it looks at thousands of stars at one time, and expects to detect hundreds of planets, Kepler will tell us for the first time about the relative numbers of large- and small-diameter terrestrial planets, down to Earth-sized, something about which we can only guess today.

**3.2 SIM** will detect planets indirectly by measuring the wobble of a star back and forth across the sky. SIM will tell us the mass of each planet, its orbital distance, its orbital shape and orientation, and the length of its year. SIM uses interferometers to measure stellar positions with respect to neighboring stars, and repeats these measurements over the full sky, many times over several years. SIM will be most sensitive to planets that are massive and have periods of several years. SIM will go well beyond the range of radial-velocity techniques, and will tell us which nearby stars have such planets, as well as the relative numbers of heavy- and light-weight planets, down to Earth-mass range around some stars.

**3.3 TPF-C** will detect and characterize planets directly by measuring a visible-wavelength snapshot image of a star-planet system. TPF-C suppresses starlight to the level where the planet stands out clearly. TPF-C will be able to tell us the visible brightness of each planet, its orbital distance, its orbital shape and orientation, the length of its year, and the amounts of life-related atmospheric gases (oxygen, water vapor, ozone, carbon dioxide, methane). In favorable cases, TPF-C potentially will be able to tell us the length of the planet's day, the amount of plant life on the surface, an estimate of ocean/land ratio, and a measure of cloud variability.  TPF-C uses a single, large-aperture telescope and a coronagraph to suppress starlight.  TPF-C will be most sensitive to Earth-like planets in the habitable zone that are in orbital positions such that their day-lit portions are visible from the Earth.  TPF-C will be able to observe planets that are, on average, smaller than the planets that Kepler, SIM, and radial-velocity techniques can reveal.  TPF-C will be designed to search for habitability and signs of life on extrasolar planets.

**3.4  TPF-I** is the infrared analog to TPF-C**.**  TPF-I will detect and characterize planets directly, using the planet's own infrared emission, independent of the orientation of the day-lit side.  TPF-I will measure an infrared snapshot image of a star-planet system in which the stellar infrared emission is suppressed to the level where the planet will stand out clearly.  TPF-I will be able to tell us the infrared brightness of each planet, its orbital distance, its orbital shape and orientation, the length of its year, the amounts of life-related atmospheric gases (water vapor, ozone, carbon dioxide, methane, and nitrous oxide).  If the planet's atmosphere is transparent enough, TPF-I may be able to tell us the length of the planet's day, an estimate of ocean/land ratio, and a measure of cloud variability.  TPF-I uses an array of four formation-flying large, cooled telescopes and a nulling interferometer to suppress the star's infrared emission. Together, TPF-C and TPF–I are a scientifically ideal pair to search for habitability and signs of life on extrasolar planets.

## 4.  Mission Connections and Synergy

The four missions, Kepler, SIM, TPF-C, and TPF-I, approach the search for terrestrial planets from different perspectives, and all perspectives are needed to determine habitability and search for signs of life.  Kepler will examine distant stars in our Galaxy, a different set than the nearby stars the latter three missions will observe, so for this reason we set Kepler aside for the remainder of this discussion.

Focusing on SIM, TPF-C, and TPF-I, we tabulate the important physical parameters that each mission can address.  We use "**Meas**" to indicate a directly measured quantity from a mission, "**Est**" to indicate that a quantity can be estimated from a single mission, and "***Coop***" to indicate a quantity that is best determined cooperatively using data from several missions. *The cooperative aspects are discussed below in italics.*  We anticipate that the strongest scientific statements about extrasolar planet characteristics will come from these cooperative measurements.

**4.1  Stable orbit in habitable zone.**  Each mission can measure an orbit and determine if it lies within the habitable zone (where the temperature permits liquid water on the surface of the planet).  SIM does this by observing the wobble of the star, and calculating where the planet must be to cause that wobble.  TPF-C and TPF-I do this by directly imaging the planet and noting how far it appears to be from the star.

*(1)  A SIM detection of a terrestrial-mass planet could provide TPF-C and TPF-I with targets to be characterized and the optimum times for observing them, thus increasing the early-mission characterization yield of TPF-C or TPF-I.*

| | SIM | TPF-C | TPF-I |
|---|---|---|---|
| **Orbital Parameters** | | | |
| Stable orbit in habitable zone | Meas | Meas | Meas |
| **Characteristics for Habitability** | | | |
| Planet temperature | Est | Est | Meas |
| Temperature variability due to distance changes | Meas | Meas | Meas |
| Planet radius | *Coop* | *Coop* | Meas |
| Planet albedo | *Coop* | *Coop* | *Coop* |
| Planet mass | Meas | Est | Est |
| Surface gravity | *Coop* | *Coop* | *Coop* |
| Atmospheric and surface composition | *Coop* | Meas | Meas |
| Time-variability of composition | | Meas | Meas |
| Presence of water | | Meas | Meas |
| **Solar System Characteristics** | | | |
| Influence of other planets, orbit coplanarity | Meas | Est | Est |
| Comets, asteroids, and zodiacal dust | | Meas | Meas |
| **Indicators of Life** | | | |
| Atmospheric biomarkers | | Meas | Meas |
| Surface biosignatures (red edge of vegetation) | | Meas | |

*(2) Where SIM finds a planet, of any mass, in almost any orbit, TPF-C and TPF-I will want to search as well, because we expect that planetary multiplicity may well be the rule (as in our Solar System). Thus SIM will help TPF-C and TPF-I to prioritize likely target stars early in their missions.*

*(3) For cases where SIM detects a planet only marginally, an important cooperative aspect is that we could use TPF-C or TPF-I to focus on the system, and verify or reject the detection. Such verification could improve the uncertainty in SIM results.*

**4.2 Planet temperature.** A planet's effective temperature can be roughly estimated by noting its distance from its star, and by assuming a value for the albedo. TPF-C can make a better estimate of the temperature by noting the distance, and using planet color to infer its albedo (by analogy with planets in our Solar System). TPF-I can observe directly the thermal infrared emission continuum at several wavelengths (i.e., infrared color), and use Planck's law to calculate the effective temperature. For a planet with a thick or cloudy atmosphere (like Venus), the surface temperature is different from the effective temperature, but might be inferred from a model of the atmosphere.

*With all three missions combined, the orbit, albedo, and greenhouse effect can be estimated, and the surface temperature as well as temperature fall-off with altitude can be determined cooperatively and more accurately than with any one mission alone.*

**4.3 Temperature variability due to distance changes.** Each mission alone can observe the degree to which the orbit is circular or elliptical, and thereby determine if the temperature is constant or varying. In principle TPF-C and TPF-I can tell whether there is an asymmetry in color or spectrum at points in the orbit, and estimate a tilt of the planet's axis, which would also lead to temperature variability due to seasons.

*The measurement of a terrestrial planet's orbital eccentricity using combined missions (SIM plus TPF-C* *and/or TPF-I) can be much more accurate than from any one mission alone, because complementary sensitivity ranges in planet mass and distance from star combine favorably.  SIM gives eccentricity data that aids TPF-C and TPF-I in selecting optimum observation times for measuring planet temperature, clouds, and atmospheric composition.*

**4.4  Planet radius.**  SIM measures planet mass, from which we can estimate radius to within a factor of 2 (assuming a value of density, which in the Solar System spans a factor of 8).  TPF-C measures visible brightness, which along with an estimate of albedo, can give a similarly rough estimate of radius; a TPF-C color-based estimate of planet type can give a better estimate of radius.  TPF-I measures infrared brightness and color temperature, which with Planck's law gives a more accurate planet radius.

*Planet radius and mass, or equivalently density, is very important for determining the type of planet (rocks, gas, ice, or combination), its habitability (solid surface or not; plate tectonics likely or not), and its history (formed inside or outside of ice line).  With SIM's mass, and one or both TPF brightness measurements, we can dramatically improve the estimate of planet radius.*

**4.5  Planet albedo.**  The albedo is important because it controls the planet's effective temperature, which is related to its habitability.  SIM and TPF-C combined can estimate possible pairs of values of radius and albedo, but cannot pick which pair is best (see above).  We can make a reasonable estimate of albedo by using TPF-C to measure the planet's color, then appealing to the planets in our Solar System to convert a color to an absolute albedo.  By adding TPF-I measurements we can determine radius (above), then with brightness from TPF-C we can compute an accurate albedo.

*SIM and TPF-C together give a first estimate of planet albedo.  Adding TPF-I gives a conclusive value of albedo, and therefore effective temperature and potential habitability.*

**4.6  Planet mass.**  SIM measures planet mass directly and accurately.  TPF-C and TPF-I depend entirely on SIM for planet mass.  If TPF-C and TPF-I do not have a SIM value for planet mass, then they will use theory and examples from our Solar System to estimate masses (see above).

*SIM plus TPF-C and TPF-I are needed to distinguish among rock-, ice-, and gas-dominated planet models, and to determine with confidence whether the planet could be habitable.*

**4.7  Planet mass sensitivity.**  To see how SIM can help TPF-C, we use a single target list of stars.  For each target star, we calculate the minimum detectable mass of a terrestrial planet in the middle of the habitable zone (see Appendix for details).  To illustrate the effective low-mass working range for each mission, we arbitrarily select the 25-percentile planet mass point (e.g., target number 35 in a ranked list for each case), and find a value of 3.9 Earth-masses for SIM, 1.1 Earth-masses for TPF-C, and sub-Earth-mass (not yet available) for TPF-I.  Therefore SIM will typically be able to find heavy-Earth planets, pointing the way for TPF-C and TPF-I to find Earth-mass and Mars-mass planets.

We can understand these mass values qualitatively, as follows.  SIM can most easily detect a stellar wobble when the planet is heavy, and the instrument's astrometric threshold is sufficiently small.  TPF-C can most easily detect a planet when it has a large reflecting surface area per unit mass (i.e., smaller diameters), and the instrument contrast threshold is sufficiently small.  TPF-I can have a smaller inner working angle than TPF-C, and so could see planets closer to the parent star. Several synergies result:

*(1) SIM might find a very massive planet in an orbit that would make it impossible for a terrestrial*

*planet to exist in the habitable zone, so TPF-C might decide to avoid these cases initially.*

*(2) Since SIM can survey many stars relatively quickly, it can produce a list of stars where habitable-zone planets are strongly or even marginally detected, and hand off this list to TPF-C and TPF-I for follow-up confirmation, and later characterization, thereby increasing the early-mission efficiency of the TPF missions.*

*(3) For SIM detections, TPF-C and TPF-I can confirm the detection and measure the planet's colors, to build up a catalog of extrasolar planet properties.*

*(4) For SIM detections that have low signal-to-noise ratios, TPF-C and TPF-I can improve the orbit parameters.*

**4.8 Surface gravity.** The planet's surface gravity is calculated directly using mass from SIM and radius from TPF-C and TPF-I (see above).

*Surface gravity is important to habitability because massive, dense planets are more likely to have plate tectonics (a crucial factor in Earth's evolution), and whether the planet can retain an atmosphere (also crucial for Earth). Cooperative measurements are the only way to obtain this data.*

**4.9 Atmosphere and surface composition.** The TPF missions are designed to measure a planet's color and spectra, from which we can determine the composition of the atmosphere and surface. For the atmosphere, TPF-C can measure water, molecular oxygen, ozone, the presence of clouds for a planet like the present Earth, and in addition it can measure carbon dioxide and methane for a planet like the early Earth or a giant planet. For the surface TPF-C can measure vegetation using the "red edge" effect (see below). TPF-I will add to this suite of observations by measuring carbon dioxide, ozone, water, methane, and nitrous oxide using different spectroscopic features, and in general probing a different altitude range in the atmosphere. SIM is important to this interpretation because it provides planet mass, crucial to interpreting atmospheric measurements.

Both TPF-C and TPF-I are needed in order to determine whether a planet is habitable, because they make complementary observations, as follows (assuming an Earth-like planet). Ozone has a very strong infrared (TPF-I) feature, and a weak visible (TPF-C) one, so if ozone is abundant, both can be used to extract the abundance as well as the thermal structure of the atmosphere, and if ozone is weak, then only the TPF-I feature will be useable. Water as seen by TPF-C will be near the surface of the planet, but as seen by TPF-I it will be in the upper atmosphere; together both give a more complete picture of the atmosphere. Methane and carbon dioxide and nitrous oxide, in small amounts (as for the present-day Earth) can be detected by TPF-I. Methane and carbon dioxide, in large amounts (as for the early Earth), can be detected by TPF-C. In addition, for large amounts of methane or carbon dioxide, TPF-I will see mainly the amount in the upper atmosphere, but TPF-C will see mainly the amount in the lower atmosphere, so both are needed for a complete picture. In addition to these "overlap" topics, only TPF-C can measure oxygen, vegetation, and the total column of air (Rayleigh scattering); likewise only TPF-I can measure the effective temperature.

*In short, SIM is needed for planet mass, TFP-C and TPF-I are needed to characterize the atmosphere for habitability, and all three are needed to fully characterize the planet.*

**4.10 Temporal variability of composition.** Both TPF-C and TPF-I potentially can measure changes in color and the strengths of spectral features as the planet rotates. These changes can tell us the length of day on the planet, and can indicate the presence of large oceans or land masses (with different reflectivities or emissivities, by analogy to Earth). Superposed on this time series of data could be random changes from weather patterns, possibly allowing the degree of variability of weather to be measured.

*The TPF missions can potentially measure variability of composition over time, which we know from our Earth to be an indicator of habitability.*

**4.11 Presence of water.** Both TPF-C and TPF-I have water absorption features in their spectra, so if water vapor is present in the atmosphere, we will be able to measure it. However habitability requires liquid water on the surface, which in turn requires a solid surface as well as a temperature that permits the liquid state; only with the help of a value of mass from SIM will we be able to know the radius, and when TPF-I is launched, the temperature.

*To know whether liquid water is present on the surface of a planet, we need mass data from SIM, spectroscopic water data from TPF-C or TPF-I.*

**4.12 Influence of other planets, orbit co-planarity.** All three missions can detect several planets around a star, within their ranges of sensitivity. Thus there may be a planet close to the star that SIM can detect, but is hidden from TPF-C. Likewise there may be a distant planet that TPF-C or TPF-I can detect, but has a period that is too long for SIM. For the more subtle issue of whether the planets have orbits in or out of the same plane, SIM will do the best job.

*In general, each of the three missions will detect some but not necessarily all of the planets that might be present in a system, so the combination will deliver a complete picture of what planets are present, their masses, their orbits, and how they are likely to influence each other over the age of the system, including co-planarity.*

**4.13 Comets, asteroids, and zodiacal dust.** Comets and asteroids have very low masses compared to planets, so will not be detected by SIM, but because they have a large surface area (for their mass) they might be seen collectively, if their numbers are high, by TPF-C in reflected light and TPF-I in thermal emission. Certainly zodiacal dust clouds will be seen easily by both TPF-C and TPF-I.

*The combination of TPF-C (visible) and TPF-I (infrared) measurements can tell us about the average albedo and numbers of solid objects (comets and asteroids), as well as ground-up material (exo-zodiacal dust). With SIM data on planets the detection of sub-planet material by TPF-C and TPF-I will produce a picture of a planetary system's history and present interactions.*

**4.14 Atmospheric biomarkers.** The simultaneous presence of an oxidized species (like oxygen or ozone) and a reduced species (like methane) is considered to be a sign of non-equilibrium that can indicate indirectly the presence of life on a planet. The presence of a large amount of molecular oxygen, as on the present Earth, may also be an indirect sign of life. In addition since water is a prerequisite for life, as we consider it here, the presence of liquid water (indicated by water vapor and an appropriate temperature) is needed. Together these spectroscopically-detectable species are our best current set of indicators of life on a planet.

*These markers will be measured exclusively by TPF-C and TPF-I, but to know that we are observing an Earth-like planet will require SIM data on mass. If we do (or do not) find biomarkers, we will certainly* *want to know how this is correlated with planet mass.*

**4.15 Surface biosignatures (red edge of vegetation).** The "red edge" is a property of land plants and trees whereby they are very good reflectors of red light (just beyond the long-wavelength limit of our eyes). This is a useful feature for measuring plant cover on Earth. If extrasolar planets have developed plant life like that on Earth, and if the planet is bright, has few clouds, and a lot of vegetated land area, then we may use this feature to detect living vegetation.

*As for other biomarkers (above), we will want to correlate the presence of vegetation with the planet mass, requiring SIM as well as TPF-C.*

**4.16 General astrophysics.**

Each mission, SIM, TPF-C, and TPF-I, will have a vigorous program of general astrophysics that will take advantage of the revolutionary advantages that these missions offer in angular resolution or deep imaging or both. Several examples of synergies follow:

*(1) Stellar Evolution. SIM can determine accurate ages of Galactic globular clusters by measuring their distances, and TPF-C can use its huge collecting area to see similar stars in local galaxies and thereby measure their ages and evolution. TPF-I with its infrared sensitivity will advance all aspects of stellar evolution from studies of star forming regions to late stars.*

*(2) Cosmology. SIM will determine H0 to much better than present accuracy, and TPF-C will take advantage of this to measure the distances to nearby galaxies. TPF-I will have the capability to probe the distant universe.*

*(3) Dark matter. SIM will measure proper motions in nearby galaxies, thereby allowing the mass of dark matter to be estimated. Building on this experience, TPF-C will be able to measure proper motions in more distant galaxies, thereby constraining their dark matter content. TPF-I will have the capability to probe the inner regions of the galaxy which will not be visible to SIM or TPF-C.*

*(4) Microlenses. Each of SIM, TPF-C, and TPF-I will be able to measure long-duration microlensing events which, combined with observations from the distant Earth, will allow the detection of (i) isolated black holes toward the center of our Galaxy, and (ii) massive remnant cores of early stars which will tell us about the early synthesis of elements.*

**4.17 Technical heritage**.

Each new mission builds on the technological heritage of earlier related missions, and in some cases that inheritance is essential. Examples follow. SIM has developed exquisitely precise methods of measuring the relative locations of optical elements in a train of optics, a technological heritage that will be beneficial to TPF-C and TPF-I. Also, SIM will be the largest interferometer flown in space, thus enabling TPF-I. In addition, since SIM will be the first space instrument to demonstrate aperture synthesis imaging, it paves the way for the next generation of dilute-aperture missions, including TPF-I. Finally, SIM has pioneered methods of accounting for wavefront uncertainties in optical systems, and also in designing technical milestones that the pre-flight development effort must meet in order to pass a series of gates; both of these systems-engineering methods will be valuable to TPF-C and TPF-I as these programs unfold.

## 5. Summary

The exploration of extrasolar planetary systems is a rich and diverse field. It calls for measurements with many kinds of instruments, as well as theoretical studies and numerical modeling. To discover and characterize extrasolar planets that are habitable and may show signs of life, and to be sure beyond a reasonable doubt that we can detect life, we need to measure the statistical distribution of planet diameters, the masses of nearby planets, and the spectra at visible and infrared wavelengths. The missions that can carry out these measurements are Kepler, SIM, TPF-C, and TPF-I. We are convinced that each of these missions is a vital element of the program. Not only does each mission by itself provide its own compelling science, but together these missions form a coherent approach that will advance our understanding better than any single one by itself.

## 6. Appendix: Planet Mass Sensitivity.

Technical details on the calculation of planet mass sensitivity for SIM and TPF-C are summarized here. Corresponding calculations for Kepler and TPF-I will be added in a subsequent white paper.

We define the ***minimum mass planet*** to be the smallest detectable planet of Earth-like density and albedo and effective temperature. Each mission has a minimum-mass planet that it can detect around each star, given the mission's specific technique and sensitivity.

For ***SIM*** the minimum detectable planet mass is M(SIM, min.) = 0.33 M(Earth)*$D/L^{0.26}$ where M(Earth) is the mass of the Earth, D is the distance to the star in parsecs, L is the luminosity of the star in units of solar luminosity (i.e., L(Sun)=1), and we have assumed SIM's Level-1 requirement that the minimum detectable amplitude of stellar wobble is 1.0 micro-arcsec (assuming a false alarm rate of only 1%).

For ***TPF-C*** the minimum detectable planet mass is M(TPF-C, min) = 0.81 M(Earth)*$L^{1.50}$ where the planet is seen at quadrature (maximum angular separation from its star), and the minimum detectable contrast ratio (planet/star) is $10^{-10}$ or 25 magnitudes.

For this letter, we select the ***target stars*** that can be seen by TPF-C according to the rules that (1) at quadrature the planet must be at least 58 milli-arcsec distant from its star, (2) the star must be brighter than V = 7, (3) the star must be closer than 30 parsecs, (4) the star must have no stellar companion within 10 arcsec, and (5) the star must be on the Main Sequence and of spectral type F, G, K, or M.

For this letter, we restrict the range of ***terrestrial planets*** to the mass range 0.5 to 10 M(Earth), a theoretically reasonable range because less massive planets will tend to lose their atmospheres quickly (like Mars), and more massive planets will tend to accumulate thick gaseous envelopes (like Jupiter). We also distribute the planets in this range in bins of equal mass size but populated as 1/M, a rule that is the same as a uniform distribution in log-mass space, as is suggested by observations of more massive planets, however this distribution is not directly relevant in calculating a minimum detectable mass.

The net result of one such calculation, using the above parameters, is that all these conditions are fulfilled simultaneously for SIM and TPF-C for a joint target list of 139 stars. For each mission, we rank the targets in terms of the minimum-mass terrestrial planet that could be detected around each star. Thus targets with the lowest-mass planet detection limit are first-rank targets. To characterize the kinds of planet masses that could be detected by each mission, we arbitrarily pick the planet in the middle of the top half of each list, i.e., the 25-th percentile planet. For SIM this planet has 3.9 earth masses, and for TPF-C it has 1.1 Earth masses. We expect that for TPF-I the threshold will be even smaller, in the sub-Earth (e.g., Mars) range.

Signed and dated on behalf of the indicated groups:

7/21/05

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