Terrestrial Planet Finder Interferometer (TPF-I)
Whitepaper for the AAAC Exoplanet Task Force

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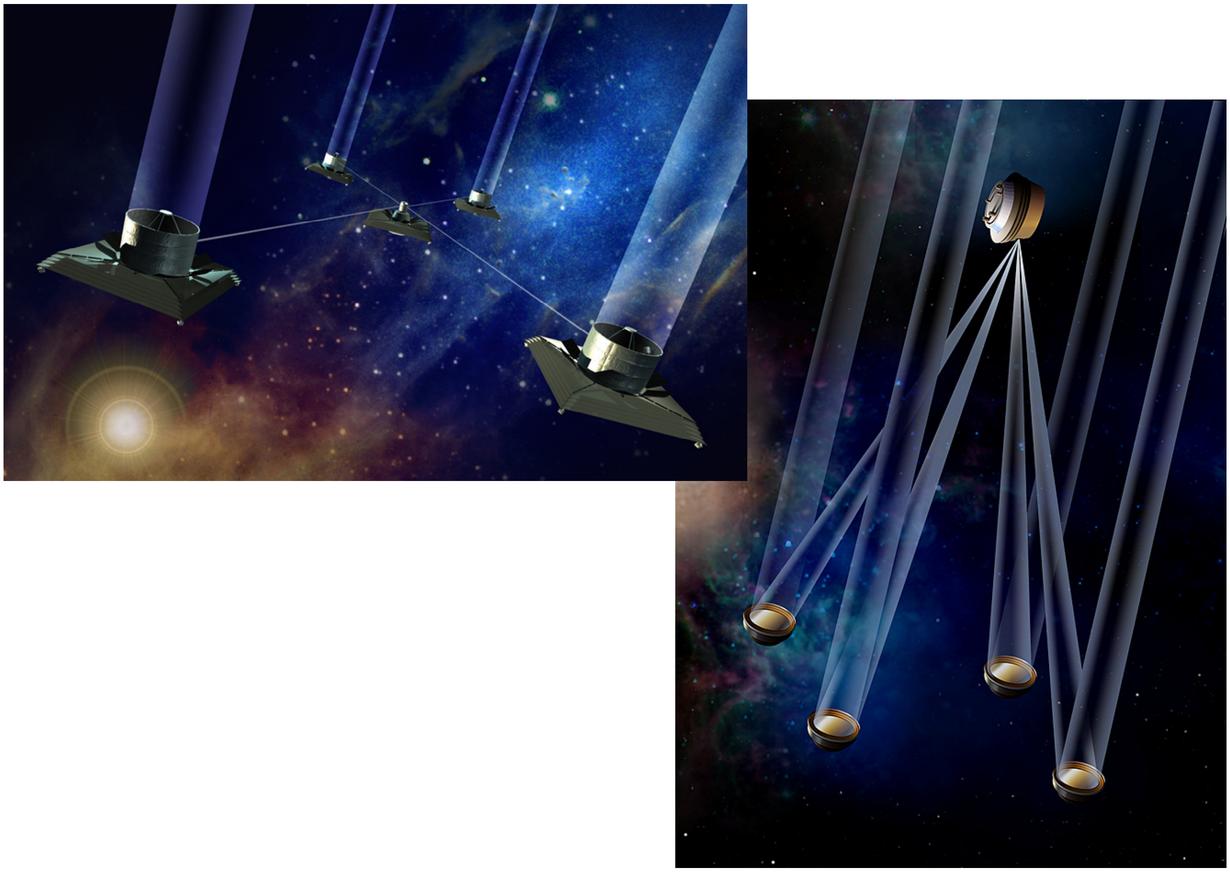

1. INTRODUCTION AND OVERVIEW

The Terrestrial Planet Finder Interferometer (TPF-I) will allow us to identify habitable planets like our own Earth around the nearest stars and to assess how common they might be. By combining the sensitivity of space-borne telescopes with the high spatial resolution of an interferometer, TPF-I will study planets beyond our own solar system in a variety of ways: from their formation and evolution in the disks of newly forming stars to the properties of planets orbiting the nearest stars; from the numbers, sizes, locations, and diversity to their suitability as abodes for life. The characterization of the size, temperature, and orbital parameters of entire planetary families, including bodies as small as the Earth in regions where liquid water might be expected to be stable, i.e. the "habitable zones," will reveal the diversity of planetary systems in our galactic neighborhood.

This whitepaper illustrates the performance of TPF-I using an "Emma X-Array" architecture, having four 2-m diameter mirrors. Compared to previous designs this architecture significantly reduces the complexity of the collector spacecrafts and offers almost full sky coverage over a year of observation. Table 1 illustrates the properties of this point design, described in more detail later in the text.

The main strengths of TPF-I are as follows: the mid-infrared provides several key biomarkers and a favorable planet-star contrast ratio; the compact inner working angle of TPF-I gives access to a very broad range of target stars; and TPF-I has unrivalled angular resolution, vital for unambiguous orbit determination, robust separation of multiple planets, and discrimination against structure in the exozodiacal disk. In these regards, TPF-I far exceeds the predicted capability of other planet-finding missions. In addition, TPF-I is being planned as a future collaboration between NASA and the European Space Agency (ESA). ESA's Darwin mission closely parallels TPF-I, and the cost of the joint mission could be shared as an equal partnership between the two agencies. Over and above its planet-finding capability, the 2000 Decadal Survey noted "there will be few areas of astrophysics untouched by the power of an infrared interferometer with the resolution and sensitivity of TPF."

2. SCIENCE GOALS AND OBJECTIVES

The major scientific objectives of TPF-I are: (1) search for and detect any Earth-like planets in the habitable zone around nearby stars; (2) characterize Earth-like planets and their atmospheres, assess habitability, and search for signatures of life; (3) carry out a study of gas giants and icy planets, as well as terrestrial planets within the 5 AU of nearby stars (at a nominal distance of 10 parsecs from the Sun) within the field-of-view of a 10-μm interferometer; (4) carry out a program of comparative planetology; and (5) enable a program of revolutionary general astrophysics. A mission lifetime of 5 years, possibly extended to 10 years, is foreseen.

The motivation to observe at mid-infrared wavelengths is threefold: the star-planet contrast is more favorable than at shorter wavelengths; there are clear biomarkers; and the optical tolerances of the observatory are relaxed. The science requirements define the characteristics of the observatory design and the mission. The facility must provide a sensitivity that will enable spectroscopic measurements of the light from the planet to determine the type of planet, its gross physical properties, and its main atmospheric constituents.

With a low-resolution spectrum covering the 6–20 μm region, TPF-I would be able to determine directly the effective temperature of the planet. Coupled with the total flux density and orbital location, TPF-I measurements also determine a planet's radius and albedo. Beyond simple

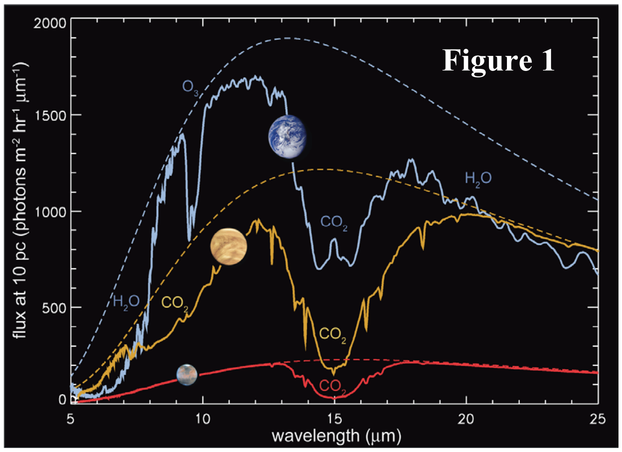
Figure 1

physical characterization, TPF-I would be able to search for potential signs of a habitable planet and signs of life itself. In the mid-IR, the most studied and robust signature of biological activity is the combined detection of the 9.6-µm O_3 band, the 15-µm CO_2 band, and the 6.3-µm H_2O band or its rotational band that extends longward from 12 µm (Selsis et al. 2002; DesMarais et al. 2002). The ozone absorption feature in the planetary thermal emission becomes detectable for O_2 levels higher than 0.1% of the present terrestrial atmospheric level (Segura et al. 2003), and can thus trace a photosynthetic biological source of oxygen. The Earth's spectrum has displayed this feature during the past 50% of the age of the Solar System. Other spectral features of potential biological interest include methane, ammonia, nitrous oxide and nitrogen dioxide, which would not be detectable by TPF-I in an exact Earth analog, but might be present in measurable quantities in a potentially habitable (or inhabited) planet at earlier evolutionary phase. Methane, for instance, was biologically sustained at a level producing a deep detectable feature at 7.4 µm during most of the period that predated the rise of oxygen on Earth (Pavlov et al. 2000), and Earth's spectrum also exhibited a deep methane feature, simultaneously with

Table 1. Illustrative Properties of a TPF-I Observatory Concept

Parameter	**4-Telescope Chopped X-Array Emma Design**
Collectors	Four 2-m diameter spherical mirrors, diffraction limited at 2 µm operating at 50 K
Array shape	6:1 rectangular array
Array size	400 × 67 m to 120 × 20 m
Wavelength range	6–20 µm
Inner working angle	13–43 mas (at 10 µm, scaling with array size)
Angular resolution	2.4 mas to 8.2 mas (at 10 µm, scaling with array size)
Field-of-view	1 arcsec at 10 µm
Null depth	10^{-5}at 10 µm (not including stellar size leakage)
Spectral resolution $\Delta\lambda/\lambda$	25 (for planets); 100 for general astrophysics
Sensitivity	0.3 µJy at 12 µm in 14 hours (5σ)
Target Stars	153 (F, G, K, and M main-sequence stars)
Detectable Earths	72 (2 year mission time, 1 Earth per star)
Exozodiacal emission	Less than 10 times our solar system
Biomarkers	CO_2, O_3 , H_2O, CH_4
Field of regard	Instantaneous 45° to 85° from anti-Sun direction, 99.6% of full sky over one year.
Orbit	L2 Halo orbit
Mission duration	5 years baseline with a goal of 10 years
Launch vehicle	Ariane 5 ECA or equivalent

ozone during a 1.5 billion year period after the rise of oxygen (Kaltenegger et al. 2007). This situation where a reduced species like methane is detected along with O_3 is a very strong indication of a biological release (Lovelock 1980; Sagan et al. 1993). The three strongest bands in the Earth-analog spectrum, O_3 band, CO_2 band, and H_2O (see Figure 1, courtesy of F. Selsis and G. Tinetti), could all be detected with a spectral resolution of 10–25. Models show that these features are present and vary in important ways in planets covering a broad range of ages and hosted by stars of different spectral types (Segura et al. 2003; Kaltenegger et al. 2007).

Contributing precursor science for TPF-I is described in detail by Lawson and Traub (2006). The highlights in precursor science will include (1) contributions from CoRoT and Kepler to our knowledge of the frequency of terrestrial planets; (2) measurements by the Keck Interferometer and the Large Binocular Telescope Interferometer of exozodiacal emission around nearby stars; and (3) measurements of the orbits of Earth-like and larger planets through SIM PlanetQuest. It is also noteworthy that spectroscopy of transiting giant planets has begun through measurements from HST and Spitzer. Spectroscopy of Earth-like planets in extreme or unusual environments (hot Earths and Earths around M-dwarfs) is anticipated in the years prior to TPF-I.

In addition to its program of planet detection and characterization, the TPF-I mission would have at least 25% of mission time available for a revolutionary program of general astrophysics, providing a sensitivity to rival JWST but with angular resolution of 1–10 mas, depending on wavelength and array configuration. As described in the recent report of the TPF-I Science Working group (Lawson et al. 2007), such a facility would make dramatic new observations in areas of: 1) Star and planet formation and early evolution; 2) Stellar and planetary death and cosmic recycling; 3) The formation, evolution, and growth of black holes; and 4) Galaxy formation and evolution over cosmic time.

3. PRINCIPLE OF OPERATION

In the mid-infrared the required angular resolution of $\leq$50 mas would necessitate a single telescope with a primary mirror larger than 40 m across, making an interferometer a compelling choice for the overall design. Nulling interferometry is used to suppress the on-axis light from the parent star, whose photon noise would otherwise overwhelm the light from the planet. Off-axis light is modulated by the spatial response of the interferometer: as the array is rotated, a planet produces a characteristic signal which can be deconvolved from the resultant time series (Bracewell 1978; Woolf and Angel 1998). Images of the planetary system are formed using an extension of techniques developed for radio interferometry.

Several interferometer implementations have been studied. A structurally-connected version with a deployable 36-m boom was studied (the maximum size that can be accommodated in the launch shroud), but the 90 mas inner working angle and poor angular resolution greatly restricted its capability for finding Earth-like planets. Tethered spacecraft were also considered and rejected. Formation-flying has become the platform of choice for both NASA and ESA, and after many years of study, the architecture for TPF-I that seems the most promising is the *X-Array*, configured in an out-of-plane geometry known as the *Emma* design.

The X-Array: An architecture trade study in 2004 favored the X-Array over other architectures (Lay et al. 2005). The X-Array is configured as two pairs of telescopes, where each pair acts as a separate nulling interferometer. The distance between telescopes in each pair therefore can be tuned to best suppress background stellar leakage around the null. Then the distance between one pair and the other can be adjusted to provide the angular resolution necessary to unambiguously isolate the light from a planet. In most other designs, the baselines for nulling are coupled with those that provide the angular resolution — and in those designs it is difficult to simultaneously suppress stellar leakage *and* have high angular resolution. The X-Array has other advantages: it uses only two types of spacecraft designs, has a simple beam-relay geometry, and its performance degrades gracefully. The X-Array also provides a means of eliminating noise due to “instabilities” in the servo systems that maintain the null. Instability in the null – the analog of speckle noise in a coronagraph – can otherwise mimic the fringe modulation due to the presence of a planet. With the X-Array design, a null depth to 10^{-5} would satisfy the flight requirements (Lay 2006).

Emma Design: ESA, as part of its design studies, considered the “Emma” architecture, shown in Figure 2. In this design the combiner is moved out towards the star by about 1 km, and the collectors are reduced to simple spherical mirrors. The Emma design offers significant advantages which are presently being studied independently by ESA and NASA. Preliminary results of these studies were first reported in the latter half of 2006. The appeal of the Emma design is primarily in its simplification of the collector optics: all deployable structures are eliminated and the layered sunshields are protected by a hard shell. The collector diameter can be scaled up or down to suit the mission performance requirements, with minimal impact on the combiner design. Overall, there exists obvious agreement in design principles between researchers at NASA and ESA, and the architectures for both TPF-I and Darwin appear to be converging in 2007.

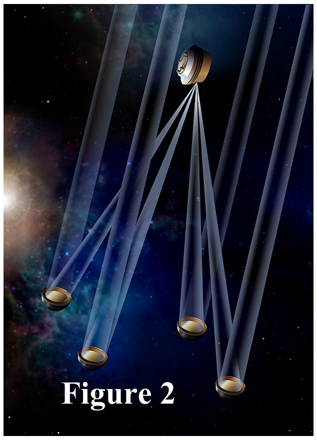
Figure 2

4. MODELING OF SYSTEM PERFORMANCE

The Interferometer Performance Model breaks down the contributions to the SNR for a single observation, including both photon noise and instability noise. Figure 3 shows the integration times required to achieve an SNR of 5 for an Earth-sized planet at the center of the habitable zone, for each of 1014 candidate target stars. Circle diameters are proportional to the intrinsic size of the star. Large circles to the upper right are F stars; small circles to the lower left are late K or early M spectral types. The array properties are listed in Table 1. In contrast to a fixed structure or primary mirror, formation-flying interferometry allows a flexible array size that can be tailored to maximize the SNR for each star. The long baselines are sufficient to resolve the habitable zone around all nearby stars. Planets are easiest to detect around nearby K stars. Integration times increase through the A and F stars as a result of the higher stellar leakage. For the Earth-Sun system at 10 pc (square symbol), 14 hours of integration time is required for detection. The Interferometer Performance Model is the source of requirements on both the flight system and the technology testbeds, and provides inputs to the mission-level model.

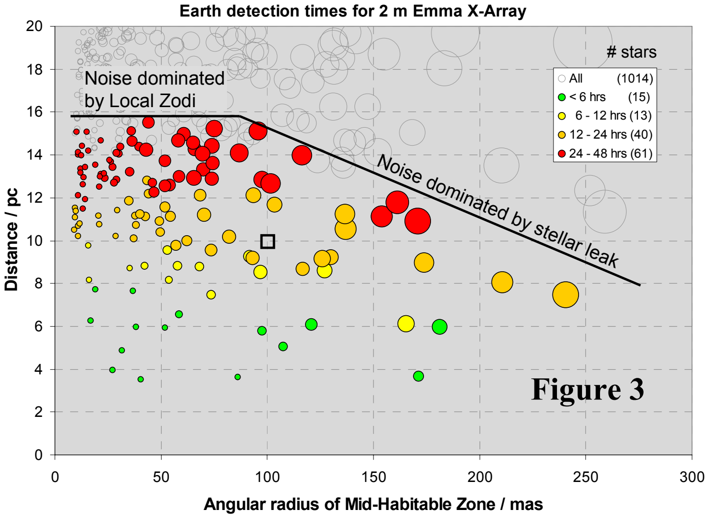

Figure 3

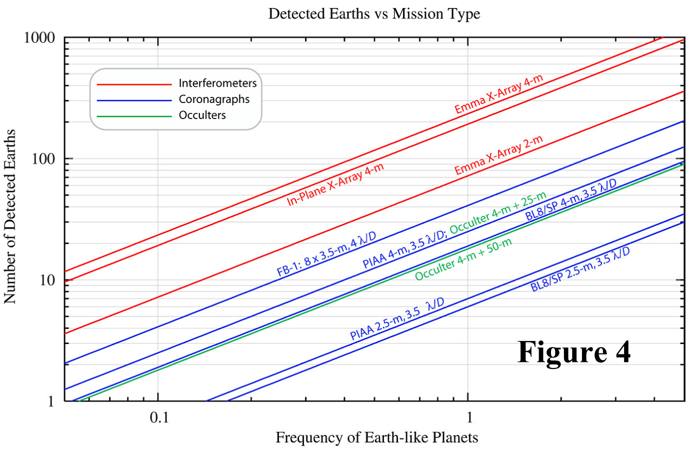

Figure 4

The mission-level model estimates the number of target stars observable in a given mission duration. The algorithm optimizes the observing schedule to maximize the number of planets found in the habitable zone. Based on the same completeness analysis developed for TPF-C, the model uses a Monte Carlo distribution of planetary orbits, includes a high-fidelity representation of the instrument, and accounts for which targets are available during each week of the mission. We assume that 2 years of the nominal 5 year mission are set aside for the initial survey, including overheads for re-targeting, calibration, etc. Each target requires only a single visit in the optimized scenario, resulting from the combination of the very small inner working angle and, in the mid-infrared, a constant planet-brightness throughout each orbit. If every star has one Earth-sized planet, randomly distributed over the range of possible habitable orbits, then an Emma X-Array with 2-m collectors can detect an average of 72 Earths by observing 153 target stars. Observations of nearby stars have a completeness close to one, i.e. almost all potentially habitable planets are detected, but as the distance increases it proves to be most productive to observe a larger number of stars at lower completeness than fewer stars at high completeness. In this case the net completeness for the survey is ~47%. For 4-m collectors the average planet yield increases to 230 with 450 targets. Figure 4 shows how these values compare with various coronagraph and occultor designs, that use the very same optimization. The lines represent the points for one Earth per star, scaled linearly to other values. The data is drawn from the Navigator whitepaper.[1]

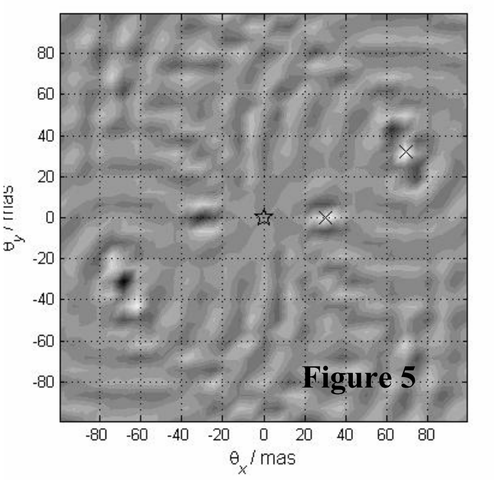

Figure 5

Candidate detections require 2–3 follow-up observations to establish the orbit and discriminate against background sources. Again, TPF-I's superior angular resolution and compact inner working angle are ideally suited to the task. The resolution of a stretched X-Array (210 × 35 m) is illustrated in the dirty map shown in Figure 5, synthesized from multi-channel observations. Planet locations are marked with an '×'; the negative

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[1] In the figure "FB-1" is the TPF-C Flight Baseline design with a 3.5 × 8 m primary and inner working angle of 4 λ/D; "BL8" is a band-limited 8th order mask coronagraph; "SP" is a shaped pupil mask coronagraph; "PIAA" is a Phase-Induced Amplitude Apodization coronagraph; the occultors shown have a 50-m shade at 72,000 km and a 20-day slew, and a 25-m shade at 30,000 km and a 6-day slew (in each case a telescope with a 4-m primary is assumed). The inner working angle in all cases is 3.5 λ/D, except for FB-1 which uses 4 λ/D. In all the examples, the yield scales linearly with the prevalence of Earth-like planets.

mirror images are a side-effect of phase chopping, and are eliminated in the deconvolution process.

Simultaneous full resolution (R~100) spectroscopy for all objects within the field of view is a natural by-product of interferometric observing. While data from the detection and orbit determination phases should be sufficient for a coarse spectrum, a deep characterization will require significant integration time. Detection of CO_2 for an Earth at 5 pc with 2-m collectors will require ~ 24 hours of integration (SNR of 10 relative to the continuum). The narrower ozone absorption line requires 16 days at 5 pc. For ozone at 10 pc, integration times as long as 40 days could be needed, falling to ~ 6 days with 4-m diameter collectors. Integrating deep into the noise for these observations is made possible by the very specific combination of modulations imprinted on the planet signal that distinguish it from the noise: a characteristic low frequency variation from array rotation, the fast switching of phase chopping, and the oscillating wavelength dependence of the interferometric response in the spectral domain.

5. TECHNOLOGY STATUS AND FUTURE MILESTONES

The primary goals of TPF-I technology development in Pre Phase A have been to (1) demonstrate mid-infrared nulling; (2) demonstrate the reliability of algorithms for formation flying; and (3) demonstrate, as funding permits, supporting technology for mid-infrared spatial filtering, cryocoolers, cryogenic systems, and integrated modeling and model validation. The technology goals reflect the flow-down of requirements from the science requirements, and meet the error budgets that have been developed for each area. More information on current TPF-I technology, including up to date testbed descriptions is available at the TPF-I website, http://planetquest.jpl.nasa.gov/TPF-I/tpf-I_index.cfm.

Nulling Interferometry: With TPF-I's current requirement of nulling at a level of 1×10^{-5}, it is clear that experiments in *laser* nulling produce results that routinely surpass flight requirements, and that *broadband* nulling experiments (with the Adaptive Nuller) have produced nulls that only fall short of flight requirements by a factor of 2. Mid-infrared laser nulling with null depths in excess of 10^{-6} has been demonstrated (Martin et al. 2003). Laser nulls of 4×10^{-6} are obtained routinely in the lab with the Planet Detection Testbed and the Achromatic Nulling Testbed at JPL. In January 2007, broadband nulling was demonstrated at a level of 2×10^{-5} by the Adaptive Nuller testbed using a 32% bandwidth centered on $\lambda=10$ μm. Interferometric planet detection has been demonstrated with a four-beam nulling interferometer (the Planet Detection Testbed) with a planet/star contrast of 2×10^{6}. Mid-infrared single-mode fibers have also been produced in chalcogenide glass, 20-cm long, showing 40% throughput and 30 dB suppression of higher order modes. Technology for mid-infrared nulling is therefore nearing maturity. A more comprehensive survey of the state of the art in nulling is available at the TPF-I website.

Formation Flying: Work on formation flying for TPF-I has focused on the development and ground-based laboratory demonstration of flight-like sensors and control algorithms in the Formation Control Testbed (FCT) at JPL. The formation flying requirements are largely independent of the requirements for nulling interferometry. Each telescope in the formation will have its own delay line, and a delay of several tens of centimeters, and perhaps as large as a meter, will be available to co-phase the array. The objective for the FCT is to (1) establish relative range control between robots to within 5 cm, 1 σ; (2) demonstrate fault-tolerant algorithms; and (3) demonstrate collision-avoidance maneuvers. The robots are now working well in cooperative testing, and should reach these milestones in 2007–2008.

6. COLLABORATION WITH THE EUROPEAN SPACE AGENCY

The science and technology teams of TPF-I and ESA's Darwin mission continue to maintain an excellent working relationship. Both groups believe that it is in their mutual interest that the projects eventually be combined in a single mission. Such a formal working relationship is some years away, and in the meantime each group is working within their own scientific and engineering communities to develop key technologies and to refine the mission science requirements; TPF-I is progressing towards the 2010 Decadal Survey report, and a proposal for Darwin is being prepared in response to the call for ESA's Cosmic Vision 2015–2025. As discussed at a number of joint meetings, the TPF-I SWG and the Darwin science team (TE-SAT) both agree on the principal aspects of the mission, including (1) the scientific goals, (2) the science requirements, and (3) the pros and cons of the two main candidate architectures. Through efforts in the near term the technical teams of TPF-I and their European colleagues are collaborating to arrive at a common architecture for the interferometer.

7. GUIDANCE ON COST

A version of TPF-I with unrivalled planet-finding capability would be possible within the budget of a flagship mission, particularly if costs were shared with ESA. Although a detailed costing is not yet available, the scope of TPF-I in its classic co-planar design clearly makes it a flagship mission. The Emma design, however, promises numerous cost savings and might permit a 2-m version of TPF-I within the scope of a mid-class mission (as described in the Navigator Program whitepaper). The ESA Cosmic Vision AO specifically addressed the issue of cost for Darwin, suggesting that it lay beyond the 650 M Euro budget cap of the "L" missions, and stated that partnership and cost sharing with another agency was required. Such a partnership has been long anticipated by the TPF-I and Darwin teams.

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