TPF-C: Status and Recent Progress

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ABSTRACT

The Terrestrial Planet Finder Coronagraph (*TPF-C*) is a deep space mission designed to detect and characterize Earth-like planets around nearby stars. *TPF-C* will be able to search for signs of life on these planets. *TPF-C* will use spectroscopy to measure basic properties including the presence of water or oxygen in the atmosphere, powerful signatures in the search for habitable worlds. This capability to characterize planets is what allows *TPF-C* to transcend other astronomy projects and become an historical endeavor on a par with the discovery voyages of the great navigators.

Keywords: Terrestrial Planet Finder Coronagraph, TPF, TPF-C, exoplanets, extrasolar planets

1. INTRODUCTION

The scientific goals of the *TPF-C* mission—to discover and study Earth-sized planets around neighboring stars—are ambitious, exciting and profound, addressing some of the most important questions humankind can ask about its place in the universe. Scientists have found a variety of giant planets, and are poised to find smaller planets, more and more like the Earth. *TPF-C* (shown schematically in Fig. 1) will be our first chance to detect large numbers of Earth-sized planets nearby, see them directly, measure their colors, study their atmospheres, and look for evidence of life there. These goals

make *TPF-C* a special project in the history of astronomy, one capable of firing human imagination and revolutionizing the way we think about ourselves and the universe.

The existence of planets around other stars, an unsupported scientific hypothesis until the mid-1990s, is no longer in doubt. Nearly 200 extrasolar planets have been discovered around other main sequence stars, most of these using the ground-based radial velocity (RV or Doppler) technique. Most of these planets found by the RV method are Jupiter-sized or larger, but several may be as small as Neptune, and the smallest one is only 7.5 Earth masses. A new planet found by gravitational microlensing may be even smaller, about 5.5 Earth masses.

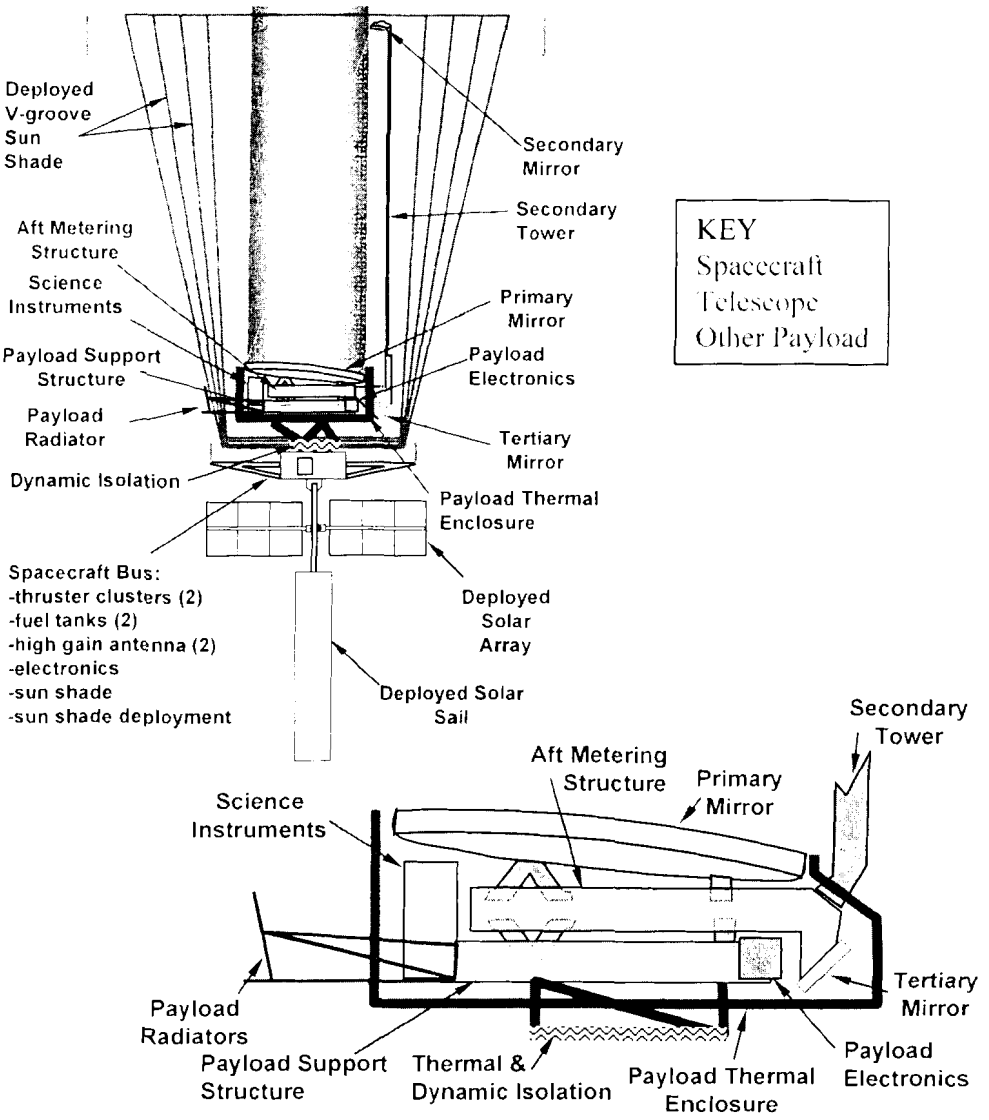

Figure 1. Schematic of TPF-C in its first full engineering study form, "Flight Baseline 1" (FB1). The purpose of FB1 was to explore engineering feasibility. The final flight design will undoubtedly differ from FB1 as more improved optical, mechanical, and thermal solutions are developed.

The next frontier for planet-finding is to look for rocky, terrestrial-type planets around other stars. NASA's upcoming *Kepler* mission* and the French *COROT* mission† will do this for more than a hundred thousand very distant stars, while the *Space Interferometry Mission*‡ *(SIM PlanetQuest)* searches around nearby stars. Both Kepler and *SIM* have the capability to detect at least a few Earth-size planets if they are common. Ongoing ground-based searches may also reveal Earth-mass planets around very low-mass stars. *TPF-C*, however, is being designed to search for and characterize Earth-sized planets (and smaller) around nearby stars. These stars span a range of masses both smaller and larger than the Sun.

How well *TPF-C* will be able to characterize the planets it discovers depends on the design of both the telescope and the spectrograph. The baseline design has a wavelength range of 0.5-1.1 μm and a spectral resolving power, $\lambda/\Delta\lambda$, of 70. For an Earth twin (planet and star exactly like our Earth and Sun) seen at 10 pc distance, these capabilities would enable *TPF-C* to measure absorption bands of water vapor, oxygen, and possibly ozone. The presence of water vapor is an indicator of potential habitability, as liquid water is considered to be a prerequisite for life as we know it. Oxygen and ozone are potential indicators of life itself, because on Earth they come mainly via photosynthesis. There may be planets on which O_2 and O_3 can build up abiotically, but for most planets within the liquid water habitable zone, these gases are considered to be reliable bioindicators. Hence, *TPF-C* is the first mission with the potential to provide compelling evidence of life on extrasolar planets. We may not answer this question definitively with *TPF-C*, but subsequent missions, specifically *TPF-I* and *Life Finder*, will probe even more deeply into this age-old question that encompasses science, philosophy, and issues of human identity and destiny.

***TPF-C* can also study giant planets and dust disks — the entire *planetary system architecture* — at the same time that it looks for Earth-like planets, supporting our studies of the potential habitability of any Earth-like planet.** If our own Solar System is a guide (it still is, by what we know today), planets like Earth are found in planetary *systems* that include other small rocky planets, *e.g.*, Venus and Mars, along with gas giants like Jupiter and Saturn, and ice giants like Uranus and Neptune. The larger planets are of interest in their own right, but they may also be crucially connected to the habitability of the Earth-like planets. In our own Solar System, for example, Jupiter helps shield Earth from collisions with comets, but also perturbs some asteroids into Earth-crossing orbits. Thus understanding the potential habitability of an Earth-like planet requires study of the entire *planetary system architecture*. Fortunately, these studies can be done at the same time as terrestrial planet-finding observations that they support.

TPF-C will also study the dust clouds around stars, to learn about the process of planetary formation. Some observations of very young stars will be included, though these stars are not favorable for the terrestrial planet search program. Planetary systems themselves do not occur in isolation around stars. Collisions between small bodies (asteroids) within the system, and vaporization of icy planetesimals (comets) from farther out both create dust that orbits the star along with the planets. This dust reflects starlight, giving rise to the *zodiacal light* in our own Solar System and to *exozodiacal light* in other planetary systems. The planets in a given system must be observed against these backgrounds of the "zodi" and the "exozodi." The exozodiacal light in a given system must be measured and "removed" in order to see the planets. However, it is also known that the dust distribution can be perturbed by the gravitational influence of planets; thus the exozodi light may be a powerful tool for finding and studying the planets in a system. For these reasons, the study of exozodiacal dust clouds is an integral part of the *TPF-C* mission. Mapping out the exozodiacal light can be carried out simultaneously with the search for terrestrial planets.

In addition to its primary goal of searching for terrestrial planets and the dusty systems that accompany them, *TPF-C* will make substantial contributions in other areas of general astrophysics. The telescope will be very large, smooth, and stable, and so will exceed the performance of *HST* in several respects, including collecting area, angular resolution, and point-spread-function (PSF) stability. To take advantage of this large telescope, a separate instrument—a wide-field camera—is planned, in addition to the coronagraph. This instrument would channel light along a different optical path, and hence could perform its tasks either in parallel with planet-finding activities or by using the telescope in pointed mode. The science that could be performed in parallel includes imaging of distant galaxies, similar to the *Hubble* Deep Fields but with even greater depth and clarity. Such deep fields could be obtained during the extended time

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* http://www.kepler.arc.nasa.gov/
† http://smsc.cnes.fr/COROT/index.htm
‡ http://sim.jpl.nasa.gov

intervals, one day to several weeks, required for planetary detection and characterization. Pointed observations will yield key constraints on theories of Dark Energy, through precise measurements of the *Hubble* constant and the distance vs. redshift relation. Observations of collections of stars in the Milky-Way and nearby galaxy will probe the "fossil record" of star formation, using stars too faint to detect with *HST* or *JWST*.

In the following sections we summarize the status of the *TPF-C* mission. The material in this paper is adapted from the Executive Summary section of a recent STDT Report[1] on *TPF-C*, edited by three of us (ML, SS, JK), with contributions from another of us (WT) as Project Scientist for *TPF-C*. The Report[1] itself was written by a large team of scientists and engineers comprising the Science and Technology Definition Team (STDT) as well as *TPF-C* Project personnel at JPL and GSFC. The STDT members are listed as authors of the present paper, and key Project members are listed in the Acknowledgements section of the present paper. The engineering, research, and writing of the Report[1] was an approximately 2-year effort, resulting in a 400-plus page volume. We intend to publish the Report later this year in a publicly-accessible form. Additional science background can be found in Ref. 2.

2. SCIENCE OBJECTIVES

The detailed science objectives for *TPF-C*, as derived by the STDT, are listed here without further discussion. The objectives are relatively self-explanatory, but the discussion that is needed to justify them in detail is well beyond the scope of the present paper. A full discussion will be found in the Ref. 1.

2.1. Terrestrial Planet Science

Objective 1: Directly detect terrestrial planets within the habitable zones around nearby stars or, alternatively, show that they are not present.

Objective 2: Measure orbital parameters and brightnesses for any terrestrial planets that are discovered.

Objective 3: Distinguish among planets, and between planets and other objects, through measurements of planet color.

Objective 4: Characterize at least some terrestrial planets spectroscopically, searching for absorption caused by O_2, O_3, H_2O, and possibly CO_2 and CH_4. It is highly desirable to measure Rayleigh scattering and photosynthetic pigments; such information may provide evidence of habitability and even of life itself.

2.2. Giant Planets and Planetary System Architecture Science

Objective 5: Directly detect giant planets of Jupiter's size and albedo at a minimum of 5 AU around solar type stars, and to determine orbits for such giant planets when possible, given the finite lifetime of the *TPF-C* mission.

Objective 6: Obtain photometry for the majority of detected giant planets, to an accuracy of 10% in at least three broad spectral bands, and in additional bands for the brightest or well-placed giants.

Objective 7: Characterize some detected giant planets spectroscopically, searching for the absorption features of CH_4 and H_2O.

2.3. Disk Science and Planet Formation Science

Objective 8: Measure the location, density, and extent of dust particles around nearby stars for the purpose of comparing to, and understanding, the asteroid and Kuiper belts in the Solar System.

Objective 9: Characterize disk-planet interactions with the goal of understanding how substructures within dusty debris disks can be used to infer the presence of planets.

Objective 10: Study the time evolution of circumstellar disks, from early protoplanetary stages through mature main sequence debris disks.

2.4. General Astrophysical Science

Objective 11: Constrain the nature of Dark Energy via precise measurements of the Hubble constant and the angular-diameter vs. redshift relation.

Objective 12: Use the fossil record of ancient stars in the Milky Way and nearby galaxies to measure the time between the Big Bang and the first major episodes of star formation.

Objective 13: Determine what sources of energy reionized the universe and study how galaxies form within dark-matter halos, through a program of low-resolution spectroscopy of large statistical samples, gathered in parallel with the *TPF-C* planet search program.

Objective 14: Carry out a diverse General-Observer program in the tradition of the *Hubble, Chandra, Spitzer,* and *James Webb Space Telescope* observatories.

3. BASIC TELESCOPE CONCEPT

The technical challenges for such a mission are great. *TPF-C* will detect planets by isolating their faint light from the glare of their host stars, using advanced coronagraphic techniques. The *Hubble Space Telescope (HST)* can also make coronagraphic observations but at a sensitivity which is far from the level required for terrestrial planet discovery. At the visible and near-IR wavelengths where *TPF-C* will operate, an Earth-like planet at an Earth-like distance from its star is roughly 10^{10} times dimmer than the star. Isolating the planet's light requires exceptionally efficient starlight suppression — eliminating nearly all the light of the star without suppressing the light of its planets. This also requires a very large-aperture telescope, both to gather enough light from the faint planets and to achieve the needed angular resolution. A schematic view of *TPF-C* is shown in Fig. 1.

In order to examine a statistically significant sample of nearby stars, *TPF-C* must be able to look at stars out to a distance of at least 10 parsecs, or about 32 light years. At that distance the host star and an Earth-like planet orbiting 1 AU away from it would be separated by an angle θ less than 0.1 arcsecond, or 100 mas (milliarcsec). *TPF-C* is designed to reach closer separations, $\theta \cong 60$ mas at $\lambda = 0.5$ μm. This inner limit is called the inner working angle (IWA). A judicious engineering choice for the baseline design of *TPF-C* limits the IWA to $\theta = 4\lambda/D$; this suggests that the diameter of the telescope should be at least $D \cong 8$ m. However, present launch vehicles cannot accommodate a monolithic 8 m *circular* telescope, nor is any such capability under development. Consequently, the baseline design for the *TPF-C* primary mirror is an 8 × 3.5 m *ellipse*, a shape and size that could be launched with present rockets.

The present baseline mission is limited by light-gathering power (photon statistics) as well as spatial resolution. Alternative and more powerful starlight suppression systems are being studied (see Sec. 8 and 9 below) that could conceivably operate at $\theta = 2\lambda/D$, and provide starlight suppression with nearly a 100% throughput. These might allow equivalent science to be undertaken with smaller aperture, or might allow a richer science program with the baseline 8 × 3.5 m aperture. However, these alternative approaches are currently less mature than the $4\lambda/D$ systems of the baseline design, for which detailed engineering analyses have been performed. The baseline design for the telescope and starlight suppression system is currently the only well-studied approach.

4. DESIGN REFERENCE MISSION

The traditional purpose of a Design Reference Mission (DRM) is to provide benchmarks of scientific output, to be used for comparing different observatory designs. The DRM comprises several kinds of observations or scientific studies, which are chosen to represent all the principal kinds of activities over the mission lifetime.

Early work on the DRM for *TPF-C* also followed this path. A key figure of merit was completeness, defined as the fraction of all possible habitable zone (HZ) orbits that are examined for the presence of a planet at least once during the mission. We can also say the probability of a false negative result for a given star (a planet does exist in the HZ but is never found) is one minus the completeness. Mission models chiefly focused on the integration time needed to reach a given planet sensitivity for each star in the catalog, the number of visits needed to achieve a certain completeness, and how many stars can be scrutinized at that level. One could compare different telescope and coronagraph architectures based on how many stars they could examine. These early studies said between 35 and 50 stars could be searched for planets, using 2 years out of a 5-year mission lifetime. Another year was reserved for characterization (mainly spectra) and 2 years for general astrophysics.

Recently, the STDT changed the focus of the requirements: from completeness goals on each star to the expected value of the total number of planets found and characterized. A mission aimed at completeness will emphasize the scrutiny of the last few unexamined orbits (hiding places for a planet) around each star. This will allocate a lot of observing time to stars already shown to have a low probability of hosting a terrestrial planet. But a mission aimed instead at the total number of discovered planets will spend its next hour(s) on the star most likely to yield a planet. Thus, over the mission, more stars will be observed, but with lower average completeness per star.

Teams at STScI and JPL expanded their mission studies to include Monte Carlo simulations incorporating a novel scheduling tool: an "auction" of observing time based on each star's "completeness rate" — estimated probability of yielding a planet per unit time, with the benefit of knowledge from prior observations. Mission studies showed a promising harvest of planets — typically 30+ planets found, assuming every star has one terrestrial planet in the HZ.

But a set of one-time planet detections cannot be called a successful mission; *TPF-C* must also characterize its planets. When examining the consequences of that mission requirement, the two teams uncovered new constraints, mainly arising from the types, scheduling, and total time of follow-up observations.

We have made substantial progress in understanding how the final scientific output depends on observatory requirements and mission scheduling. Now we understand that *TPF-C*, more than any previous space astronomy mission, relies on just-in-time contingent scheduling of observations to achieve its greatest scientific harvest. This is mainly because many of the exo-planets we find will be a surprise, and then their orbital motions limit the times when we can see them again. We will have some prior knowledge about which local stars have terrestrial planets — mostly heavier planets, found by *SIM-PlanetQuest*. The *Kepler* mission will only give us an estimate of the *fraction* of local stars with terrestrial planets, based on a sample of distant stars. Smaller or more distant terrestrial planets will be undetected or poorly known before *TPF-C*. Our Monte Carlo studies show that when we detect a planet for the first time, we may have as little as two weeks to wait before its orbital motion makes it unobservable again — too faint, or too close in angle to the star. This means we must be quick to schedule a follow-up observation. There are several reasons why follow-up observations are vital: (a) Differentiating between planets and background confusion sources. (b) Low-resolution color measurements, to categorize the type of planet. (c) Orbit determination, to distinguish small inner planets from large outer planets, and to help characterize their habitability. (d) Higher-resolution spectroscopy, to search for atmospheric signatures of water, oxygen, and other molecules.

The same Monte Carlo studies suggest that once a planet disappears, due to either brightness or angular separation, it can be very difficult to find again. We must use our best chances, right after the first detection, to constrain the possible orbits and thus the range of times it might reappear. This "recovery" of the planet after its first disappearance plays an important role in characterization.

The recent mission studies incorporating these impacts now tell us that the FB1 system may not be adequate for the new science requirements the STDT has just adopted. This gap between capabilities and requirements is understandable, given the history. There has been no design team available to trade off different ways of relieving the gap. But it appears that modest changes to the FB1 engineering requirements may be sufficient to close this gap. This analysis will have to wait for rejuvenated funding.

Some additional work has been focused on how to "front-load" the observing schedule with stars which are known to harbor planets, either from *SIM-PlanetQuest* astrometric detections of small rocky planets or from giant planet detections (by any method) which suggest the possible existence of small rocky planets. Some stars may yield tentative detections by *SIM-PlanetQuest* that can be confirmed and strengthened by *TPF-C* detection and characterization. This is a very useful additional guideline in the design of a mission observing schedule.

5. FLIGHT BASELINE DESIGN (FB1)

The current design for the *TPF* Coronagraph, Flight Baseline 1 or FB1, operates in visible wavelengths from 0.5 μm to 1.1 μm with an effective inner working angle (IWA) of 65.5 mas or 4λ/D, an outer working angle (OWA) of 500 mas, a

scattered light level equal to 10^{-10} of the stellar peak brightness ($\Delta mag_i = 25$), and stability or knowledge of that scattered light to about 6% ($\Delta mag_s = 28$). The mission will operate in an L2 orbit over a 5 year life cycle.

The observatory design requires a high precision optical system in order to provide a stable, high-quality wavefront to the coronagraph. The starlight suppression system (SSS) is a stellar coronagraph designed to eliminate diffracted light and control scattered light, in order to reduce the background light in the instrument to a level that is less than 10^{-10} of the incident starlight. For FB1, diffracted light is removed with a Lyot-type coronagraph from the region in the image plane where planets might be found. Other approaches, such as the shaped-pupil coronagraph, are currently under consideration and might be viable options for further design implementations of *TPF-C*.

In FB1, scattered light is controlled using a coarse deformable mirror (DM) and a pair of fine DMs. The coarse DM compensates for large wavefront deviations left in the telescope due to gravity release and launch stresses. The fine DMs have a 1 micron stroke and high actuator density; as a pair they can control both amplitude and phase wavefront distortions up to a spatial frequency limit determined by the actuator density, i.e., a minimum of 2 actuators per controlled spatial wavelength.

The telescope has an 8 × 3.5 m elliptical primary mirror with a system effective focal length of 14 m. The field of regard is only 5 arcsec, and the field over which aberrations must be corrected is further reduced through the use of fine steering and deformable mirrors inside the coronagraph. The distance between the primary and secondary is 12 m at the vertex and the focus is close to the middle of the primary aperture.

The observatory needs to reject both thermal and jitter perturbations at an extreme level. Thermal stability is accomplished with large deployable concentric conic-shaped v-groove layers which shed the solar heat input and isolate the payload from changing sun angles during observational maneuvers; a thermal enclosure around the payload actively controls temperatures in the back end of the telescope. Jitter stability is provided through a two-stage passive isolation system which offers the required vibration reduction from the reaction wheel disturbances. Alternatively, an active, non-contact isolation and pointing system capable of providing significant performance margin is being considered.

This FB1 design is the second in a series of 3 to 4 design iterations expected to be completed prior to entering Phase A. Each cycle will lead to a progressively more detailed design while continuously investigating options to improve and optimize performance. For FB1 the design reflects updated science requirements with a $4\lambda/D$ inner working angle, impacting the size of the primary and the design of the occulting mask. The FB1 analyses investigated the thermal and jitter impact on the contrast stability requirements, assessed contributors to the static and dynamic error budgets and scoped out requirements for the active thermal control system. In subsequent design cycles, the engineering team will incorporate models from the Instrument Concept Studies (ICS, see Sec. 8 below), improve the contrast capability of the starlight suppression system, add fidelity to the active thermal control system and optimize the system performance of the end-to-end observatory.

6. *TPF-C* PERFORMANCE DRIVERS

The performance requirements for *TPF-C* begin with adequate suppression of starlight. An ordinary telescope allows starlight to spread across the angular width of the entire planetary system, overwhelming the faint signal of the planet (typically ten billion times fainter than the star). We know by analysis and experiment that *TPF-C's* advanced coronagraph features—pupil and field masks to suppress diffraction, and deformable mirrors to suppress starlight scattered by wavefront errors—can successfully control both types of stray starlight from $4\lambda/D$ to almost $50\lambda/D$. The goal of 10^{-10} suppression in this region is at the heart of the "static error budget". It is important that the number 10^{-10} is chosen only partly to keep the background photon rate small and integration times low.

The observation strategy is the principal reason to aim for 10^{-10} suppression. The residual starlight contributes a speckle background which can vary by 100% in the width of the point spread function ($\sim\lambda/D$). To distinguish these speckles from true planets, we compare two images of the planetary system taken with a different "roll" orientation—rotation around the optical axis. This pair of images is called an observation. Through the roll maneuver, speckles are expected to

stay fixed on the telescope and thus on the focal plane, while the planet stays fixed on the sky and moves on the focal plane, rotating around the star image. During an observation, the speckle brightness pattern must be stable to much less than the expected planet brightness, so that the image subtraction will unambiguously distinguish speckles from planets.

This requires a new performance budget governing all sources of variation in the speckle brightness pattern. An important consequence of establishing this "dynamic error budget" is the fact that it places the most stringent constraints on the static error budget. The brighter a speckle is at the start of an observation, the smaller a thermal or mechanical disturbance it takes to change the speckle's brightness by 2×10^{-11} (or whatever 1-σ planet sensitivity floor we might choose).

These two error budgets have been drawn up and are described in Ref. 1. Most of these requirements have been shown to be feasible, either in the laboratory or by detailed analyses of the FB1 concept, summarized next.

7. FB1 PERFORMANCE ASSESSMENT

The major result of our FB1 modeling work is that the environmental perturbations during operation appear to be controlled sufficiently— both thermally and dynamically— to ensure that the image plane contrast remains stable to the required levels. The current sunshade isolates the telescope and payload adequately. Active vibration control easily isolates the payload from reaction wheel vibrations. Passive vibration isolation control could be effective, but it would require more tuning and would provide less margin. Vibrations from mechanisms in the instruments and starlight suppression system have yet to be included, but selective damping seems feasible and promising. The next engineering design cycle will include these.

An important feature of this area is that the commercial thermal and dynamic analysis software have limitations that are becoming well understood, and the team has implemented patches where appropriate to produce credible results. For longer term production mode use, better integrated modeling tools are being developed. These will provide parallel code architectures for much improved analysis cycle time, efficient inter-operability between the multi-physics analyses (thermal, structural, dynamics, controls and optics) and numerical algorithms required for high accuracy solutions.

Our analysis and modeling have shown that the baseline wavefront control system with realistic optical specifications cannot provide truly broad-band contrast suppression. We have learned how to modify the dual-DM wave front controller to perform better over a broad band while relaxing wave front and reflectivity uniformity requirements. The new design also reduces the number of optical components in the system. These changes will be incorporated in the next design cycle.

The baseline primary mirror concept is a thin monolithic ULE face sheet fused to lightweight ULE honeycomb core cells and mounted on 3 rigid supports. This has the potential to meet all operational requirements, but more consideration of fabrication, ground handling and testing accommodations is needed. The FB1 launch loads are too severe around the mounting points, for example. This complex assembly will need further development to address the full range of difficulties it will face. Furthermore, the FB1 observatory mass margin is too low for the capability of the chosen EELV launch vehicle. FB1 was not focused on mass optimization but significant improvements have already been identified and will be applied to the next engineering design cycle.

Within FB1 the active thermal control system was simplified to include only heaters (with no feedback) as locally applied power within the thermal enclosure. FB1 was purposely focused only on meeting those requirements of the active control system, rather than including detailed features which are not yet well understood. The goal was to use FB1 to understand how difficult and challenging the active control system will be before addressing how it should be implemented. FB1 sensitivity analyses defined the heater location, power levels and cycles required for maintaining the thermal stability of the observatory. This information will be used in the next cycle to design a higher fidelity representation of the active thermal control system.

Conclusions from the FB1 design and analysis cycle, along with open trades for possible design alternatives, will guide the next design cycle toward better performance and deeper detail. The team and community have gained significant knowledge through this exercise and will continue to do so as they await the start of the next design iteration, FB2.

8. INSTRUMENT CONCEPT STUDY REPORTS

In February 2005, NASA HQ solicited proposals for several Instrument Concept Studies (ICS) for *TPF-C*, as part of the ROSES 2005 NRA. In June 2005, five groups were selected to conduct concept studies of a variety of instruments that might be built for *TPF-C*. The selected proposals were: (1) **PIAA-AHA**, an instrument for starlight suppression, planet detection, and spectroscopy, using two novel techniques (PI: R. Angel, O. Guyon); (2) **Visible Nuller**, instrument for starlight suppression and planet detection (PI: M. Shao); (3) **Mag30Cam**, a wide-field camera for general astrophysics (PI: R.A. Brown); (4) **CorECam**, a simple coronagraph camera with color filters (PI: M. Clampin); (5) **CorSpec**, an integral field spectrometer for spectroscopic study of planets in the coronagraph (PI: S. Heap). The reports of these five teams are summarized briefly below and at length in Ref. 1.

8.1. PIAA/AHA Alternative Coronagraph

This is an instrument with integrated star suppression system for imaging and spectroscopy of terrestrial exoplanets. It combines the PIAA (Phase-Induced Amplitude Apodization) method to reach an inner working distance of $2\lambda/D$, (see below) with AHA (Anti-Halo Apodization). AHA is a new interferometric technique to sense the phase and amplitude of the residual starlight halo, and to suppress it by destructive interference with explicitly created anti-halo speckles. The two methods in conjunction promise not only the improved inner working distance, but much higher sensitivity by covering a 360 degree field without the losses in resolution and flux inherent in the baseline Lyot system. The instrument also incorporates dichroic mirrors to allow simultaneous full spectral coverage from 0.5–1.5 microns. The combined effect of increased throughput, resolution, field cover and bandwidth is more than an order of magnitude reduction in integration time compared to the baseline design. This combined with closer inner working angle allows for a much richer observing program. It should be noted that if this approach is adopted for *TPF-C*, the *HST-JWST* paradigm in which instrument teams are selected independent of the telescope is no longer applicable. This is because the science imaging and spectroscopy and the star suppression and wavefront correction systems are necessarily completely integrated, with the same imaging arrays providing the science, wavefront and speckle nulling data. A silver lining of the extended *TPF* delay is the time it opens up for development of the powerful PIAA and AHA technologies to the technology readiness level needed for a Phase A selection.

8.2. Visible Nuller

The visible nuller (VN) together with the post coronagraph calibration interferometer is being studied because it provides potential gains in several areas. The nuller has the potential to have an inner working angle of $2\lambda/D$, significantly expanding the number of potential targets. The detection of oxygen in the atmosphere of an Earth-like exo-planet is a key goal and a nulling coronagraph at $2\lambda/D$ has ~7 times more potential targets than one at $4\lambda/D$. The post coronagraph calibration interferometer (PCCI) is an equally important, perhaps even more important development. The PCCI relaxes the required wavefront stability of the telescope by about a factor of 1000, from a few picometers per hour to a few picometers per 3~4 seconds. The PCCI has two functions: (1) to measure the wavefront with very high accuracy and high photon efficiency, to ~30 picometer in ~2 minutes for a ~5 magnitude star; this is needed to set the deformable mirror to create the 10^{-10} dark hole; and (2) to measure the post coronagraph speckle pattern to 3~10% so that the ~10^{-10} residual speckle pattern can be subtracted in post processing to ~ 10^{-11}, in order for a 10^{-10} planet to be detected with a SNR of 5~10. The PCCI is being used in a number of ground and space coronagraphic instruments: a nulling coronagraph on a sounding rocket to launch in 2007; the Gemini Planet Imager, the first of the second generation instruments for the Gemini telescope; and the Planet Formation Imager, an extreme AO coronagraph for the Thirty Meter Telescope (TMT).

8.3. Wide-Field Camera

A wide-field camera (WFC) enriches the science return from *TPF-C*. Even a field of view (FOV) of only 10 square arcminute would be mostly unaffected by scattered light from stars in the coronagraph. In parallel observing mode, while carrying out planet observations, the WFC would obtain images of the deep cosmos at no cost of observing time. In pointed observing mode, it would extend *Hubble*-type imaging to 24 times greater sensitivity and 3 times better resolution. A 50 sq. arcmin FOV in a wedge shape extending to 10 arcmin off axis would produce a parallel survey of 10 sq. deg of sky to below 30th magnitude, which is 1000 times more cosmic volume than the various *Hubble* deep fields and more sensitivity than any of them. A WFC with an FOV of 10-100 sq. arcmin for the wavelength range 400–1700 nm is compatible with the baseline design for *TPF-C*. Its scientific potential would be unrivaled by any currently planned telescope on the ground or in space. A WFC is a low-risk, high-benefit option for *TPF-C*. It would effectively double the mission value at marginal cost. Recognizing the scientific benefits of such a camera, the STDT has incorporated it into the minimum, baseline, and desired mission requirements.

8.4. CorECam

The CorECam instrument concept study addressed the requirements and science program for *TPF-C*'s primary camera. CorECam provides a simple interface to the Starlight Suppression System (SSS) provided by the *TPF-C* Project, and comprises camera modules providing visible and near-infrared (NIR) focal plane imaging. In its primary operating mode, CorECam will conduct the core science program of *TPF-C*, detecting terrestrial planets at visible wavelengths. CorECam additionally provides the imaging capabilities to characterize terrestrial planets, and conduct an extended science program focused on investigating the nature of the exo-solar systems in which terrestrial planets are detected. In order to evaluate the performance of CorECam, we developed a comprehensive, end-to-end model using OSCAR modeling software, which provided a number of key conclusions on the robustness of the *TPF-C* baseline design, and allowed investigation of alternative techniques for wavefront sensing and control. The CorECam team recommends photon counting detectors be baselined for imaging with *TPF-C*, since they provide mitigation against the background radiation environment, improve sensitivity, and facilitate alternative wavefront-sensing and control (WFSC) approaches.

8.5. CorSpec

The coronagraphic spectrograph (CorSpec) team explored an instrument concept that would fulfill all four scientific objectives of *TPF-C* by: (1) Spectrally characterizing the atmospheres of detected planets; (2) Directly detecting terrestrial planets in the habitable zone around nearby stars; (3) Studying all constituents of a planetary system including terrestrial and giant planets, gas and dust around sun-like stars of different ages and metallicities; and (4) Enabling simultaneous, high-spatial-resolution, coronagraphic spectroscopy of AGNs, supernovae, and other objects requiring high-contrast spectroscopy. The instrument concept consists of a set of four integral field spectrographs (IFS), each covering a spectral band ~22% wide, and together covering the full spectral range of *TPF-C*. Each IFS has a 134 x 134 microlens array to obtain a R~70 spectrum of each Nyquist-sampled image element in the coronagraphic field, and each uses a photon-counting charge-multiplication CCD to record the ~18,000 spectra. This concept assumes that the *TPF-C*'s starlight suppression system is similarly composed of four independent units, each optimized for a given spectral band, and that each unit is capable of suppressing the starlight to an acceptable level over a passband 22% wide. The CorSpec team also developed a preliminary concept design of the starlight suppression system.

9. ALTERNATIVE MISSION DESIGNS

In addition to the basic concepts used in FB1, several alternative concepts, with the potential to improve performance and simplify the design, have been proposed. These include changing the telescope from the present Richey-Chretien design to a three-mirror astigmat (TMA), actuating the primary mirror, and two alternative starlight suppression concepts (captured in the VN and PIAA/AHA studies and their reports). It may also be possible to employ aluminum coatings on the primary and secondary mirror to enable UV astrometry with the general astrophysics instrument (GAI). The baseline telescope is a Richey-Chretien design with a small diffraction-limited field of view. The field is adequate for planet detection over several arcseconds, but it is not designed for wide-field imaging. A TMA, on the other hand, can be designed for a field ~ 10 arcmin in diameter, sufficient for the GAI. It may also have the advantage of relaxing the

positional stability tolerances on the optics. It may, however, require a radical repackaging of the starlight suppression system (SSS).

A major issue confronting the baseline design is the manufacture and on-orbit gravity release of the primary mirror, which may be as large as several microns. The baseline design includes a coarse deformable mirror (DM) to compensate the sag. But the sag is problematic for the GAI, which does not have its own wavefront control system. An alternative approach under consideration is an actuated primary mirror instead of the coarse DM. Actuation could take the form of a small number of force actuators to correct a few large-scale modes, enough to bring the residual wavefront error within the dynamic range of the fine DMs in the SSS. A more radical approach would be to build the primary as a ~ 1 cm thick meniscus connected via ~ 10^4 position actuators to a lightweight welded ULE structural support. The telescope wavefront would be corrected against deformation of the support by the primary mirror actuators, eliminating the baseline arrangement of coarse and fine deformable mirrors, conjugated to the primary. This approach would require significant technology development. Suitable piezo actuators could be developed from the current DM concepts or from existing commercial actuators with 50 pm readout and 10 micron stroke. Further study is required to understand and develop solutions for athermalizing and reducing the mass of the actuators, and for the transition from the launch to operational environment. In addition, concepts are needed to reduce the mass of the cables across the 8 m aperture.

The baseline mission design SSS carries both a Lyot coronagraph and a shaped pupil coronagraph. The Lyot coronagraph uses an eighth-order mask that, like the shaped pupil, is very effective at rejecting thermally-induced changes to low-order aberrations in the system. The baseline carries several masks optimized for discovery and characterization for different stellar classes. However, none of the masks are useful at inner working angles much below $4\lambda/D$. Alternative SSS concepts have already been mentioned: the PIAA and visible nuller. Each also has an associated concept for wavefront sensing and control which might be applicable to Lyot and shaped pupil systems.

10. VERIFICATION APPROACH

Because of its large size and extreme stability requirements, *TPF-C* poses significant challenges for pre-launch verification. To date, planning for Integration and Test (I&T) has concentrated on the Optical Telescope Assembly (OTA). It is considered to be the most challenging task because testing to the required on-orbit precision may be beyond the capability of facilities that we expect to be available. Specifically, it may not be possible to test end-to-end performance of *TPF-C* on the ground because its extraordinary performance requirements will only be achieved in zero-gravity and in an extremely stable thermally environment.

The baseline solution is to devise an approach that combines test and analysis in ground-based testing to verify on-orbit performance requirements. Component requirements will be verified directly by testing to the highest level of assembly possible, and additional tests will be performed to verify the analytical models of each component. These component models will be assembled to form the verified system model, in a manner parallel to the hardware assembly and verification process. The extent to which requirements will be inferred by analysis rather than by direct measurements will be driven by considerations of cost and risk that have yet to be addressed. As a minimum, we know that for the baseline primary mirror our ability to relieve gravity sag and to duplicate on-orbit thermal and vibration environments will most likely fall far short of what is necessary to directly verify the flight requirements; for this reason, analytical methods will be required to infer flight performance from ground test data. The final system test will therefore be limited to verifying alignment workmanship and to correlating system model parameters, by overdriving the input thermal and jitter environment.

During the FB1 cycle, integration and test plans were sketched out for the primary mirror assembly: the necessity of extreme, nanometric precision, when combined with the mirror's very large size (8.5×3m) and flexibility, poses major challenges. Plans call for figuring and final measurement of the primary mirror to be performed on the best zero-G mount possible, however, this is not necessarily compatible with flight mounting schemes. On the high fidelity zero-G mount, the mirror will be subjected to mechanical and thermal loads while its optical performance is measured with an interferometer at the center of curvature. These measurements are as faithful as can be achieved on the ground to the on-orbit performance of the mirror— they will be used as inputs to the integrated structural-thermal-optical model. After the mirror is integrated with its flight support to the Aft Metering Structure (AMS) and the Payload Support Structure (PSS),

a different gravity unloading scheme will have to be used. It is assumed that this setup will not be as effective as the high fidelity zero-G mount used before. Thermal and dynamic loading will be applied in order to observe their effect on the assembled sub-system with its flight mount. These data will be used to correlate model parameters, and the model will then be exercised in a simulated flight environment to analytically predict on-orbit performance. These analytical results will then be compared to the requirements for verification.

The alternative and most definitive verification approach is of the complete *TPF-C* spacecraft system prior to launch. An off-axis collimator would be used to illuminate the full aperture with a scene of a star and planet at 10^{-10} contrast, and the ultimate proof would be to see an image showing the planet obtained by using all the internal wavefront control and star suppression systems working as on orbit.

A test like this of the baseline design would not be possible, because of uncorrectable gravity bending of the primary in the spacecraft configuration. But it would in principle be possible for the alternative primary described above, with high authority position actuators. The stroke of the actuators would be matched to the bending of the integrated reference structure, so the primary figure could be corrected under 1 g load as well as in space. Local quilting of the facesheet would be small and of high frequency, and would not spoil such a test. The collimator would need to have a clear aperture and be off-axis, like the primary, but its optical quality need not be significantly better than that of the primary. The spacecraft star suppression system would take care of the residual collimator wavefront errors along with those of the primary. As noted above, such a test would be successful only if the vibration and thermal environment were adequately controlled. The test facility would have to be designed from the ground up with these requirements in mind. We recommend that a feasibility study for the complete test facility be included when *TPF* funding again becomes available.

11. KEY TECHNOLOGIES, DEVELOPMENT PLAN, AND RECENT PROGRESS

Planet detection, characterization, and verification are the core drivers of the *TPF-C* technology efforts, particularly in the early phase. In order to mitigate the technical risk, *TPF-C* has developed a detailed technology plan which lays out the scope, depth and inter-relatedness of activities that will enable the project to demonstrate sufficient technology maturation to enter into Phase A. Specifically, there are four milestones which require testbed demonstrations of critical starlight suppression technologies as well as validated testbed models and error budgets. These milestones are not intended to be all-inclusive, but rather to serve as benchmarks of progress. Testing of Milestone 1 for demonstration of narrowband starlight suppression at 1×10^{-9} contrast has been completed, and testing of Milestone 2 has begun for demonstration of broadband starlight suppression. Milestone 3a and 3b will validate starlight suppression models and will demonstrate flight system performance.

The challenge is to control diffracted light over a broad spectral range while mitigating the effects of internal and external errors. Technology development is organized into six areas that address aspects of this challenge. They are: (1) Fabrication of a pathfinder demonstration mirror that establishes the state-of-the-art in fabrication of large, off-axis, low-scatter mirrors; (2) Development of a starlight suppression testbed which tests various masks, deformable mirrors, wavefront sensing and control approaches, and starlight suppression algorithms; (3) Investigation, analysis and fabrication of more advanced masks and stops; (4) Development of modeling tools that will represent the extreme precision needed to model the test beds and the flight system so that feasibility for the mission can be understood; (5) Development of testbeds to investigate alternative architectures for starlight suppression; (6) Precision materials properties measurements.

11.1. Technology Demonstration Mirror (TDM)

The requirement for the *TPF-C* primary mirror allocates error for the surface quality in terms of spatial frequency, and the Technology Demonstration Mirror (TDM) was defined to study the ability to fabricate a mirror which meets the lower spatial frequency requirements. The TDM is a 1.8 meter diameter mirror composed of six outer core segments and one inner hexagonal core segment. Each segment is composed of a honeycomb core with a thin front and back facesheet. Fabrication of the TDM using low temperature slumping and fusing techniques will demonstrate whether state-of-the-art technology can meet the spatial frequency requirements. The effort will also provide methodologies to measure the

performance of the mirror and to interpret the measured data for requirements verification. Owing to funding cuts, the TDM effort has been put on hold with 2 of the core segments completed.

Trade studies have resulted in the selection of light-weighted, fuse-bonded ULE as the substrate material. The ULE boules being used have tight requirements on coefficient of thermal expansion (CTE) and have been selected to meet these requirements. Calibration standards to measure the CTE of the selected boules were re-measured to verify calibration and that the CTE requirements were met. Coating the mirror will be a challenge because coating uniformity requirements are tight. Non-uniform coatings will cause amplitude errors that will interfere with the starlight suppression requirement. In addition, polarization effects of the candidate coatings are being studied to understand the polarization effect on starlight suppression, as well as to develop concepts for mitigation of the induced polarization of the light.

11.2. High Contrast Imaging Testbed

The heart of the coronagraph system is the starlight suppression system that includes wavefront sensing and control components, as well as various masks and stop elements. The High Contrast Imaging Testbed (HCIT) enables the exploration of starlight suppression methods and hardware in a flight-like environment within which various concepts for masks and stops designs, wavefront sensing approaches, and control algorithms are being investigated. The testbed layout is flexible so that alternate concepts can be tried and guest investigator testing is available. The testbed is installed in a vacuum chamber and has been measured to have milli-Kelvin thermal stability and Angstrom wavefront stability. A series of increasingly mature and robust deformable mirrors have been developed, fabricated, calibrated and installed to demonstrate precise wavefront control.

Current narrow-band performance has reached an average contrast of $<1\times10^{-9}$ throughout both the outer working angle of $4\lambda/D$ to $10\lambda/D$ and the inner working angle of $4\lambda/D$ to $5\lambda/D$ using laser light at 785nm as specified in the technology Milestone 1 definition. Moving toward the goal of technology Milestone 2, current broad-band contrast has reached an average contrast of about 1×10^{-8} over the same areas at 785 ± 10 nm. Following that, the testbed is scheduled to explore alternate mask options and broad-band wavelength performance improvements.

11.3. Mask and Stops

Developing mask and stop forms, researching candidate mask materials and their related influences, and modeling light propagation and sensitivity to form errors are areas of research supporting the contrast goal of 10^{-10} required to detect and characterize Earth-like planets. We have developed models of polarized light propagation through masks that include electromagnetic field effects and wave band performance. Such models are used to guide mask fabrication sensitivity requirements. Modeling and assessing sensitivity has led to development of a promising new mask form called an 8th order mask. Two types of 8th order masks have been built to demonstrate this mask form, using High Energy Beam Sensitive (HEBS) glass and a deposited aluminum binary representation. These masks are scheduled for testing in the HCIT. Materials research has focused on careful measurement of material properties and influences on the mask performance. This research is expected to lead to mask solutions that increase the bandwidth of performance and polarization tolerance of future masks.

The *TPF* Coronagraph will rely heavily on modeling and analyses throughout its mission lifecycle. Thus developing models, validating them, and implementing them are a key task for the project. Current modeling activities can be separated into 3 broad areas: predictions of on-orbit performance, analytical tool development in support of specific Coronagraph needs, and verification and validation of the analyses. Development of on-orbit performance models includes modeling the thermal and dynamic responses of the observatory during operation in space. These models are tied to optical performance models that represent the propagation of the wavefront through the perturbed surfaces, including diffraction, polarization, mask and stop effects, and optimization algorithms for the deformable mirrors. Broad-band wavelength effects are being added.

11.4. Modeling and Simulation

Process verification and validation will be performed on the HCIT and future testbeds that are envisioned as the mission progresses. Optical performance modeling is being carried on the HCIT to verify contrast sensitivity to various error contributors, with the goal of validating a testbed error budget which parallels the flight system error budget. Also under

development is a fully integrated modeling tool that simulates under a single computational code the thermal, mechanical, control and optical performance of the flight system. This tool has structural evaluation, embedded thermal radiation and conduction capabilities, a NASTRAN native input format for the model description, scalability to very large problems with very efficient numerics, seamless interface to optical analysis codes, and eventually end-to-end sensitivity and optimization abilities. This tool has been used to run simple trade studies for the *TPF-C* modeling team.

11.5. Alternative Starlight Suppression Testbeds

Three additional methods of starlight suppression are being supported by *TPF-C*. A testbed has been developed at Princeton University to design, analyze, fabricate and test pupil plane masks. A testbed has been developed as a joint effort of NOAO and University of Hawaii to build and study a pupil re-mapping concept. Finally, a testbed has been developed at JPL, using visible light and interferometric techniques to create a null over a star, enabling imaging of orbiting planets.

11.6. Precision Material Properties Measurements

A critical step in predicting *TPF-C* system performance is to use material data of the highest accuracy and precision. The JPL Dilatometer laboratory is a state-of-the art facility which measures thermal strains from room temperature to 20 K at an accuracy of about 2 ppb. Active thermal control allows the samples to maintain a stability of 5 mK for as long as necessary, allowing the measurement of thermal relaxation, a form of dimensional instability and material nonlinearity. Such capability is required to measure variations in CTE distributions in ULE or nonlinear behavior of Zerodur. The JPL tribometer is also being designed to study the physics and material properties of sub-Coulombic friction as a function of temperature, pre-load and interface materials. This is an immature field which is critical for the representation of deployment mechanisms along the optical path.

12. CONCLUSIONS

When it eventually flies, *TPF-C* will be one of the most scientifically exciting missions ever launched by NASA. A positive indication of extraterrestrial life, or even the detection of a habitable planet similar to Earth, would alter the way in which humans look at themselves and at the universe. Most of the technology required to perform this mission already exists. The parts that do not, especially the coronagraphic techniques required to achieve 10^{-10} starlight suppression at close distances to the star, can likely be developed over the next year or two, given a modest amount of funding. We hope that this report will help provide the motivation to finish off these development tasks and to get the *TPF-C* mission itself restarted in as short a time as possible.

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