Terrestrial Planet Finder – Coronagraph (TPF-C)
4m Telescope Mission Concept
ASTRO2010 RFI#2

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1. EXECUTIVE SUMMARY

TPF-C has invested nearly 6 years gaining in-depth understanding of approaches and trades in formulating space-based exoplanets missions based on state-of-the-art coronagraph science instruments and sensing methods. Terrestrial planet imaging mission system formulation has progressed by advancing critically enabling technologies while developing integrated system designs and conducting system level engineering trades that assess and selectively infuse those technology advances. At the heart of progressing TPF-C mission formulation are a talented group of people with a rich experience base, that have developed and validated sophisticated exoplanet modeling tools for detailed mission performance analyses, difficult optical diffraction propagation analyses and rigorous system performance error budgeting. During this half decade of TPF-C mission formulation, some critically enabling technologies have evolved considerably to enable their inclusion into the observatory system design. Specifically, laboratory demonstrations have proven the ability to suppress light to Earth detection levels using a band-limited coronagraph [11]. This has switched the goal from proving the feasibility of Earth imaging coronagraphs, to optimizing such a mission for performance and cost. Most recently, additional NASA-funded advances in coronagraphic sensing technologies have demonstrated considerable near-term promise for higher performance coronagraph science instruments, opening the door to further evolving and refining the TPF-C system from its 8m x 3.5m TPF-C Flight Baseline 1 (FB1) point design of 2005. Parametric cost models show that overall mission cost is most sensitive to and primarily driven by telescope mirror diameter, regardless of the type of coronagraphic instrument(s) to be considered. Hence pursuing approaches that can perform exciting new exoplanet imaging science using smaller diameter space telescopes has become of special interest to NASA. In conjunction with advances in critical starlight suppression technologies, sunshield technology matured for JWST is also applicable to TPF-C for the deployment and performance of its V-groove sunshade.

Herein, we describe the highlights of a smaller TPF-C that leverages those promising advances in coronographic imaging technologies by scaling down TPF-C to a 4m circular monolithic Primary Mirror Assembly (PMA). "***TPF-C 4m***" advances the flight readiness of the mission, reduces its cost, and promises exciting new space-based exoplanet discovery science, comparable to that of TPF-C FB1, while also advancing new space-based 4m class general astrophysics imaging and spectroscopic science capabilities in the UV/Visible bands post Hubble Space Telescope (HST).

We identify the characteristics of a ***TPF-C 4m*** that scale down from the elliptical 8m x 3.5m TPF-C FB1 concept, with the same 500nm diffraction limited imaging performance operating in visible wavelengths near room temperature operations. The circular 4-m off-axis telescope design will leverage technology advances that enable the use of a more aggressive coronagraph science instrument with a smaller inner working angle (IWA) of $2\lambda/D$ to compensate for the smaller telescope size and with higher throughput to compensate for the reduced collecting aperture area. Novel $2\lambda/D$ high throughput coronagraphs are currently being developed that are good candidates for ***TPF-C 4m***. These are the Phase-Induced Amplitude Apodization (PIAA) and the Vector Vortex (VV) coronagraphs, first proposed by Guyon [14] and Mawet [15] respectively.

For the purpose of comparing mission capability, we assume for now that the science goals of ***TPF-C 4m*** remain the same as established for TPF-C FB1 with its two primary science instruments, a Coronagraphic Sensing Instrument (CSI) (which includes a starlight suppression subsystem, a camera and a spectrometer) as well as a Wide Field Camera (WFC). Because the smaller 4m PMA significantly reduces overall system volume and mass resource needs, this smaller ***TPF-C 4m*** allows a future critical mission system trade study that considers the practicalities of staying a small flagship class mission (lower cost, earlier flight readiness) against the potential science growth of a large flagship class mission that reallocates the resources (mass, power, volume, cost) to additional science instruments. We have not conducted this critical trade study at this time, though outline and frame its key parameters and considerations herein. The TPF-C FB1 science, design and performance are presented in detail in a companion TPF-C FB1 RFI#2 to the ASTRO2010, and are not repeated here. There are also many shared technologies between the TPF-C FB1 and 4m. We identify herein the strengths and weaknesses of a ***TPF-C 4m*** in comparison to TPF-C FB1, and propose trades and analyses that should be performed to assess the performance of the mission concept. We also discuss a technology maturation approach which builds on commonalities of probe scale to flagship internal coronagraph missions with off-ramps depending on the science goals and size of the mission.

The notion of a 4m design for TPF-C was first considered in 2006, just as NASA Headquarters put the TPF-C mission on indefinite hold. Hence, ***TPF-C 4m*** has been thought through and roughly defined, but has not benefited from detailed investigations, trades, modeling and analyses needed to fully understand and define its design, risks, costs and development plan as well as to credibly estimate its performance capabilities for exoplanets discovery. However, the results of this preliminary concept study provided herein show that considering more fully a ***TPF-C 4m*** system design has compelling merits well worth pursuing near term.

2. SCIENCE OVERVIEW

2.1 SCIENCE OBJECTIVES

The science objectives for ***TPF-C 4m*** remain the same as for TPF-C FB1, and are repeated here from the TPF-C FB1 RFI#2 for clarity (Table 1). Items 1-10 address exoplanetary system science, and items 11-14 address general astrophysics science. Please refer to the TPF-C RFI#2 for details of the science requirement.

For exoplanet systems, the measurement requirements are (1) the ability to make visible-wavelength images of planets and zodiacal dust in the angular range from about 0.06 to 1.00 arcsec radius around a nearby star, with the diffracted and scattered light from that star suppressed to a background noise level of about 10^{-10} times that of the star, or 25 magnitudes fainter, and (2) the ability to obtain a spectrum of any point in that field with a spectral resolution of about 70, and preferably all points simultaneously, across the entire range from 0.5 to 1.1 μm wavelength.

TPF-C also offers solid general astrophysics capabilities as the successor to the HST in the visible wavelength range. As such, it will exceed HST in angular resolution, collecting area, and faint magnitude limit. TPF-C can be characterized as a visible-wavelength HST optimized for exoplanet observations. For general astronomy, the measurement requirements for the wide-field camera comprise a pointed and a parallel program simultaneous with coronagraphic observations. In a five-year mission, parallel observations could produce a survey of at least 10 deg^2 of sky to beyond 30^{th} magnitude. Such a survey would comprise 1000 times more cosmic volume than the various Hubble deep fields and achieve greater sensitivity than any of them. Pointed observations could extend Hubble-type imaging to fainter and more distant galaxies, records of star-formation in nearby galaxies, and star-forming regions in our own galaxy.

Table 1 Summary of TPF-C Science Objectives

Science	#	Objective
Terrestrial Planet Science	1	Directly detect terrestrial planets within the habitable zones around nearby stars or, show they are not present.
	2	Measure orbital parameters and brightnesses for any terrestrial planets that are discovered.
	3	Distinguish among planets, and between planets and other objects, through measurements of planet color.
	4	Characterize at least some terrestrial planets spectroscopically, for O2, O3, H2O, and possibly CO2 & CH4.
Giant Planets & Planetary System Architecture	5	Directly detect giant planets of Jupiter's size and albedo at a minimum of 5 AU around solar type stars, and determine orbits for such giant planets when possible
	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.
	7	Characterize detected giant planets spectroscopically, searching for the absorption features of CH4 and H2O.
Disk Science and Planet Formation	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.
	9	Characterize disk-planet interactions with the goal of understanding how substructures within dusty debris disks & infer the presence of planets.
	10	Study the time evolution of circumstellar disks, from early protoplanetary stages through mature main sequence debris disks.
General Astrophysics (examples)	11	Constrain the nature of Dark Energy via precise measurements of the Hubble constant and the angular-diameter vs. redshift relation.
	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.
	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.
	14	Carry out a diverse General-Observer program in the tradition of the *Hubble, Chandra, Spitzer,* & *JWST* observatories.

A possible modification to this design may be evaluated to determine the feasibility of UV capability for general astrophysics, although not for exoplanets.

2.2 PAYLOAD PERFORMANCE REQUIREMENTS

The top level performance requirements derived from the science goals are identical to the ones formulated for TPF-C FB1 and summarized in §2.4 and §2.5 of the companion RFI#2 response.

While the contrast goals and allocations for TPF-C FB1 and ***TPF-C 4m*** are the same, observing planets at the second airy ring (~ $2\lambda/d$) with a 4m PMA is overall more challenging than observing at $4\lambda/d$ as is the baseline for TPF-C FB1. Here are our initial assessments of some of the key similarities and differences between the two mission designs.

Performance Similarities of TPF-C FB1 and *TPF-C 4m*:

- It is important to note that a 4m aperture operating at 2 λ/D provides the same IWA as an 8m aperture operating at 4 λ/D. Hence, both TPF-C FB1 and ***TPF-C 4m*** are achieving the same inner working angle (IWA) on the sky at about 60 mas depending on wavelength.
- The necessary optical quality of the primary mirror (PM) and secondary mirror (SM) is comparable between the two mission concepts, and is well within current technological capabilities. The optical systems in both can be allocated 10's of nm of residual design wavefront error, and this can be solely on the PM or SM or distributed between the two.

- For both designs, the requirements on the instrument optics are much tighter than on the PM and SM, because acceptable surface errors for the instrument optics are driven by beam walk (lateral shear of the beam across the optics causes by thermal or dynamic perturbation) and need to be allocated in the 1-2 nm regime.
- The allowed random motion of optics, mainly driven by thermal effects, is a few nm and nanoradians for both mission concepts.
- Rigid body pointing errors of the spacecraft are also comparable between the two mission concepts, at about 10 mas. This value is also driven by beam walk.
- The size of the starlight suppression instrument along with the deformable mirrors and wavefront sensing control system is independent of the telescope size, and is essentially the same for FB1 and ***TPF-C 4m***..
- The Vector Vortex (VV) coronagraph at 2λ/D shares the same Lyot optical configuration as any of the Band-limited (BL) mask methods used on FB1, with a comparable number of optical surfaces. As a matter of fact the starlight suppression instrument could have a filter wheel or comparable mechanism that switches between VV and BL on either FB1 or ***TPF-C 4m*** should that be desirable, with no significant impact on the system design. The PIAA coronagraph is more complex with the need for a pair of aspheric PIAA optics and additional re-imaging optics, for either the FB1 or TPF-C 4m mission concepts.

Performance Differences between TPF-C FB1 and 4m:

- The two systems are vastly different in their sensitivity to deformation of the optics (e.g. focus, coma, astigmatism) and back-end pointing (alignment of the stellar image on the coronagraph mask). Whereas FB1 uses an 8th-order band-limited Lyot coronagraph, ***TPF-C 4m***, achieves the same IWA with a 2λ/D coronagraph such as the PIAA or the VV that behave more like a 4th-order mask. With FB1, the requirement on the stability of focus, astigmatism, and coma, is about 20-40 pm. For ***TPF-C 4m*** with a 2λ/D coronagraph these requirements are 10 times tighter. It is for this reason that a low-order wavefront sensor [18] that can discriminate these modes on a rapid time scale, is required with the ***TPF-C 4m*** design.
- The systems are even more sensitive to higher order bending modes, e.g. spherical aberration. FB1 requires about 5 pm of stability while ***TPF-C 4m*** must be 10 times more stable, assuming all other design features are constant between the two mission concepts. The performance of the fine-guiding mirrors is another case where the smaller 4m telescope has tighter requirements. For FB1, the formal requirement in the error budget was 0.6 mas r.m.s on the sky for these bending type error sources. For the ***TPF-C 4m***, the requirement will likely need to be below 0.1 mas r.m.s on the sky, (4 mas at the coronagraph mask).
- A benefit of the 2λ/D coronagraph is its factor of 2 higher throughput of 90% compared to 45% for the 4λ/D Band-limited Lyot coronagraph. This compensates for the smaller mirror diameter of the 2λ/D coronagraphs.
- While the quality of the PM and SM is the same for both designs, it will fall on the Deformable Mirrors (DMs) to provide finer actuator control to achieve the 10 times tighter wavefront requirements for ***TPF-C 4m***.
- Because ***TPF-C 4m*** is expected to be stiffer, owing to its smaller PMA and more compact anticipated packaging, gravity release once on orbit will not require the use of a second coarse DM as exists on FB1, and could become a source of error budget reallocation from the FB1 design.

2.3 WAVEFRONT STABILITY REQUIREMENTS

Based on preliminary analyses of the performance differences between an 8m FB1 and a ***TPF-C 4m***., stability of the wavefront to thermal and jitter perturbations during an observation will likely be the most demanding challenge for ***TPF-C 4m.*** Stability requirements are about 10 times more relaxed on TPF-C FB1 because the latter operates at the 4th Airy ring at 4λ/D. Stability requirements imposed on the mission design is solely driven by the choice of the inner working angle (2λ/D vs 4 λ/D) and the contrast to be achieved, and not by the size of the observatory. This means that at the other end of the scale compared to smaller missions, we expect that ***TPF-C 4m*** at 2λ/D has exactly the same stability requirements as a 1.4m concept with a PIAA coronagraph at 2λ/D as was proposed for PECO (PI Guyon) [19]. In the case of the 1.5m concept for ACCESS (PI Trauger) [20], the stability requirements are relaxed only because the mission does not target Earths, but larger Jupiter-like planets which can be imaged with a contrast of 10^{-9} instead of 10^{-10} required for Earths. Table 2 summarizes the stability requirements for FB1, ***TPF-C 4m*** and PECO and shows the impact of the IWA on requirements. The PECO mission study showed through detailed thermal and jitter analyses, that the tighter stability requirements were achievable with passive thermal and jitter control [19]. As will be discussed later, for ***TPF-C 4m*** we baseline a two-stage passive vibration isolation system which is thought to provide sufficient margin and has high TRL and low risk. However future analytical studies of ***TPF-C 4m*** high-fidelity inter-related models are needed to determine performance and if needed active control can be implemented on ***TPF-C 4m*** for additional margin. There are several active isolation options available. One option is to use piezo actuated mounting struts, such as ITT's AIMS design, which is currently considered to be at TRL6. Another option is to use magnetic bearings, such as LMA's DFP design, which is currently considered to be at TRL5.

Table 2: FB-2 Stability Requirements (3-sigma)

Specification	**TPF-C FB1** (8m x 3.5m at 4 λ/D) Passive Isolation	**TPF-C 4m** (4m at 2 λ/D) **2-stage Passive Isolation**	**PECO** (1.4m at 2 λ/D) Passive Isolation
Wavefront stability allocation for low order optic deformations (e.g., focus, astigmatism, comma)	30 nm	3 nm	3 nm
Wavefront stability allocation for high order bending modes (e.g., spherical aberration)	5 nm	0.5 nm	0.5 nm
Backend instrument pointing (r.m.s, onto mask, after FSM)	0.6 mas	0.1 mas	0.1 mas

In general stability specifications get more difficult to achieve with larger, less stiff systems. The FB1 and PECO concepts use passive isolation and analyses showed that the thermal and jitter stability specifications could be met, with margin. In both cases, active isolation was studied and shown to provide additional margins of at least one order of magnitude.

The PECO study produced a solution to the tight backend pointing specification that closes a high rate control loop around a FSM with a low order wavefront sensor (LOWFS), using light reflected off the coronagraph mask. A breadboard of this sensor has demonstrated the required performance operating in a breadboard coronagraph system [18].

2.4 OBSERVATIONAL SCENARIO AND TECHNICAL IMPLEMENTATION

TPF-C 4m will be operated in essentially the same manner as TPF-C FB1 in a L2 Halo orbit. One benefit of ***TPF-C 4m*** is the ability to cancel at least three of the six prescribed 30 degree rolls. These three rolls are required on TPF-C FB1 to synthesize a circular image from the elliptical primary mirror. At a minimum one additional role will be required on ***TPF-C 4m*** for speckle subtraction, a.k.a "roll deconvolution". Overall this provides a significant reduction in the mission overhead from the time needed to perform the roll maneuvers and to settle afterwards to recover the required jitter and thermal stability for the observation. Furthermore, the operational scenario for ***TPF-C 4m*** provides a more stable environment and this is especially important at lower inner working angles since observatory stability requirements become more challenging.

Observation Time

The ***TPF-C 4m*** collecting area is 57 % that of FB1. SNR is background limited by zodiacal light and integration times are inversely proportional to the square of collecting area. Thus, ***TPF-C 4m*** integration time per exposure is 3 times that of FB1. However, because FB1 has an asymmetric aperture, exposures are required at 3 different roll angles to take full advantage of the axis with minimum IWA. These two effects cancel out. Also, the instrument throughput for ***TPF-C 4m*** is about twice that of FB1, so the total search mode integration time is only slightly reduced. Eliminating the settling times after each roll maneuver gives a further advantage. When characterizing a planet with known location, multiple roll angles are not necessary for FB1. Therefore, ***TPF-C 4m*** requires total characterization mode integration times that are about 2.5 times longer than FB1. How the total integration time changes for some variable mix of search mode and characterization mode is not clear without more detailed analyses.

2.5 PRELIMINARY MISSION CAPABILITY ASSESSMENT

For the purpose of this study, we assume that ***TPF-C 4m*** will operate at an L2 Halo orbit with nominal mission duration of 5 years and consumables planned for 10 years. Like TPF-C FB1, it is capable of observing 125 nearby stars over 3 years elapsed time, using only 1 year of integration and overhead time. Figure 1 compares the cumulative detection completeness for Earth-like planets of various exoplanet mission concepts, that is how many Earths are expected to be detected in a 3 year period assuming that η_{earth} = 1. We show the performance of various TPF-C options as a function of size (8mx3.5m elliptical (FB1), 4m circular and 2.5m circular) and IWA ($4\lambda/D$ and $2.5\lambda/D$). ***TPF-C 4m*** at $2.5\lambda/D$ shows approximately the same detection capability as TPF-C FB1 at $4\lambda/D$, while ***TPF-C 4m*** at $4\lambda/D$ still provides the ability to detect about half as many earths. It is also shown that ***TPF-C 4m*** can detect twice as many planets as an equivalent external occulter mission with a similar 4m telescope, but at the added cost of a second external occulter spacecraft. For all the internal coronagraph options, most of the planets are revisited several times, some with as many as twenty revisits. This is not the case for the external occulter approach. Finally, ***TPF-C 4m*** is also optimal in making use of the full detection capability provided by a precursor astrometric mission such as SIM, although it is not required.

Clearly, designs with smaller IWA provide better detection capability for the same telescope diameter. Since mission cost is driven primarily by the telescope diameter parameter, it follows that a ***TPF-C 4m*** at about $2\lambda/D$ is an attractive approach. Furthermore the exoplanet science can be accomplished at the 4m scale without the additional expense of a separate external occulter. However, coronagraphs operating at smaller IWA pose challenges on observatory stability, as will be explained later and have yet

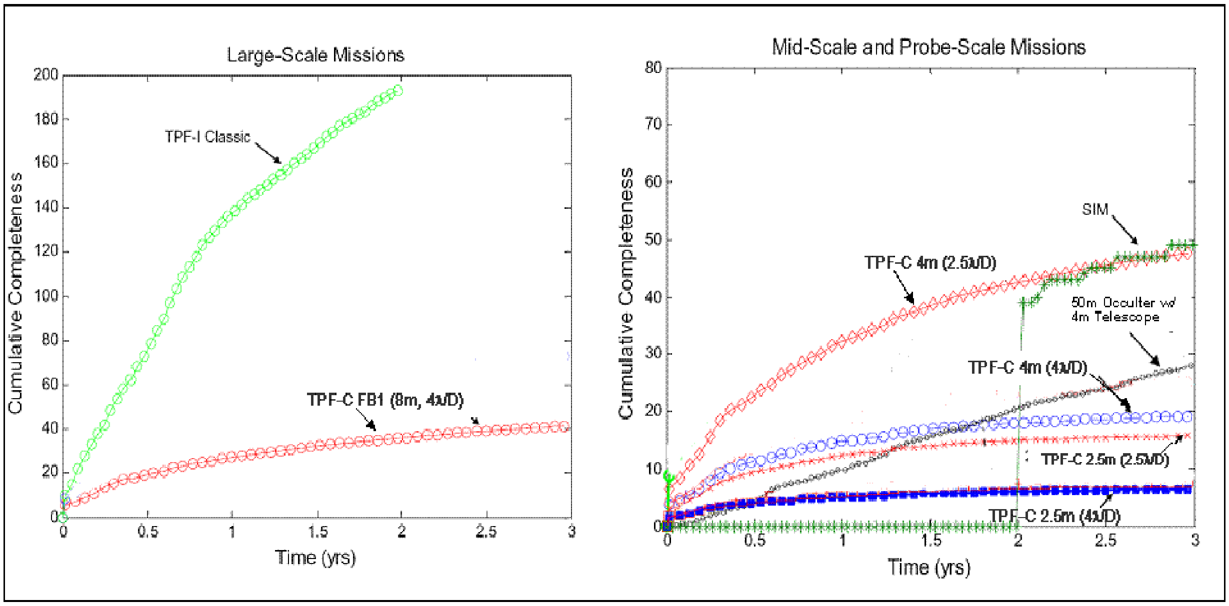

Figure 1 Comparison of the cumulative completeness for Earth-like planets for various exoplanet mission concepts over a 3-year mission span (Hunyadi, 2007).

been demonstrated to Earth-detection levels in the laboratory as has already been done at 4λ/D. Nonetheless should the need arise, internal coronagraph missions operating at 4λ/D can still offer very appealing exoplanet science even at the 4m scale and provide a less risky design alternative. Implementation options for ***TPF-C 4m*** may well even consider the possibility of using two coronagraphs, one operating comfortably with margins at 4λ/D and the other operating at the margins at 2λ/D. This can be achieved with no major cost or risk impact with a BL and a VV switched through a filter wheel or other mechanism, as they both share identical optical configuration, wavefront sensing and control and camera.

These conclusions are supported by more recent and independent simulations performed by Cahoy et al. (2009) [13] for the science evaluation of the Pupil-mapping Exoplanet Coronagraphic Observer (PECO), a medium scale 1.4m exoplanet mission proposed by PI Guyon using an aggressive Phase-Induced Amplitude Apodization (PIAA) coronagraph operating at 2 λ/D [14].

While the effective inner working angle on the sky of TPF-C FB1 and ***TPF-C 4m*** remain the same at about 60 mas depending on wavelength, the ability to achieve these goals on ***TPF-C 4m*** will be constrained by the collecting area of the aperture. However, this constraint is offset by the higher instrument throughput provided by the more aggressive coronagraph and by no longer having to roll the telescope to synthesize a circular image from an elliptical aperture such as TPF-C FB1. This constraint has no impact on the detection phase of the mission (Figure 1), however preliminary estimates indicate this may increase the characterization phase by about a factor of two to accomplish the same science as the larger telescope. A possible option could be to lengthen the mission life, either as a baseline lifetime or as a preplanned lifetime extension, to preserve the characterization capabilities provided by TPF-C FB1, the cost of which is clearly offset by the cost savings of the much smaller observatory. A more thorough Design Reference Mission (DRM) study is required to more accurately assess the impact on science and mission duration.

3. TECHNICAL IMPLEMENTATION

For the purpose of this preliminary study we offer a ***TPF-C 4m*** design which retains as much of the features of the original TPF-C FB1 concept in order to provide a direct comparison between the two options. However, we will highlight areas where ***TPF-C 4m*** offers unique advantages and identify options to be studied later should funding become available to complete a thorough mission design.

3.1 LAUNCH VEHICLE

Although many components become significantly lighter with the ***TPF-C 4m*** option, for now we assume that it will be launched on a Delta IV-Heavy, as is TPF-C FB1. However, we acknowledge that this choice of launch vehicle (LV) provides ample mass margin, which could be applied to improving the stability of the ***TPF-C 4m*** observatory and buy down the technical risk posed by the increased stability requirements at $2\lambda/D$. In future studies we would evaluate an alternative LV is the Atlas 551 with 3000 kg less throw capability to L2 at a savings of about $300M for launch services. Other concept studies have demonstrated that a 4m observatory can be launched on an Atlas V launch vehicle, with comfortable margin. The trade between either LV needs to be further evaluated, as the additional cost posed by providing aggressive thermal and jitter control to a light-weighted system, including the implications of ground testing, may well outweigh that of the heftier launch vehicle.

In either case, the LV shroud provides enough volume to launch the observatory without any significant deployments, other than a sunshield deployment that is conceptually much simpler than that being undertaken by JWST. This is a major advantage over TPF-C FB1 which had several challenging deployments to the telescope and the v-groove sunshade. Observatory deployments were identified as one of the 3 main risks in the TPF-C FB1 mission concept, and are no longer a major concern or a primary technology development need for ***TPF-C 4m***.

3.2 PAYLOAD INSTRUMENTATION

3.2.1 Telescope

The most attractive benefit provided by ***TPF-C 4m*** is its smaller non-deployed telescope, with a 4m diameter off-axis primary mirror and approximately 6m long non-deployed secondary mirror tower. Compared to TPF-C FB1 this offers obvious advantages for fabrication and testing, not to mention cost and launch load survivability concerns. As pointed out previously, the smaller mirror means reduced risk due to gravity release of the PM on orbit, among other considerations. This should alleviate the need for the coarse DM stage required on FB1, further reducing complexity and risk. There will still be an active secondary mirror mostly for pointing and alignment. The telescope is diffraction limited at 500nm with HST class surface figure requirements in the 10's nm.

As for TPF-C FB1, the baseline material for the primary mirror (PM) is Corning ULE©, selected for its low thermal expansion and stability at room temperature. The overall PM architecture will be composed of the same hexagonal segments designed for FB1 with a continuous facesheet, fused together with the demonstrated process of Low Temperature Fusion (LTF). The only difference is that fewer segments will be required, approximately ten (10) to fifteen (15) segments depending on size compared to the twenty-one (21) 1.2m segments proposed for TPF-C FB1. Preliminary estimates show that it would also be possible to increase the density of the PM from the baseline 50 kg/m^2 to possibly as large as 80 kg/m^2 while not exceeding the mass margin required for the LV. The additional mass could be used to possibly improve allocations for some terms of the wavefront stability error budget, although it would come at the cost of increasing thermal transient settling times after slews. This trade would benefit from detailed analyses to compare the performance and the mission overhead as a function of mirror density. In either case the proposed PM density range is well within the SOA for mirror fabrication and no new mirror technology or severe light-weighting is required.

3.2.2 Coronagraph Sensing Instrument

As for TPF-C FB1, the Coronagraph Sensing Instrument (CSI) on ***TPF-C 4m*** is composed of the starlight suppression system (SSS), the coronagraphic camera and the spectrometer. The camera [12] and the spectrometer [16] are identical to those in TPF-C FB1. The SSS includes the 2λ/D high performance masks/mirrors, the wavefront sensing and control (WFSC) and the deformable mirrors (DM). The technologies for WFSC and DMs are identical to those used on TPF-C FB1. The only difference with FB1 is the SSS implementation at 2λ/D with either a PIAA or VV, in lieu of a BL at 4λ/D for FB1. As explained before, architecturally this has minimal impact on the instrument whereby PIAA requires several more optics including a pair of aspheric mirrors, while the VV is indistinguishable from the traditional Lyot coronagraph architecture. This similarity also applies to smaller scale mission implementations such as PIAA system on the 1.4m PECO (PI Guyon) or the VV on the 1.5m ACCESS (PI Trauger). On PECO, PI Guyon has proposed the addition of a Low Order Wave Front Sensor (LOWFS) for the PIAA coronagraph [18].

Overall, the size and design of the SSS is independent of mission size, whether it is a probe-scale mission or a flagship. Furthermore, it is also important to note that the SSS performance is only driven by the contrast goal and its spectral bandwidths set by the target exoplanet and not by the size of the mission, that is 10^{-10} contrast in 10% wavelength bands between 0.5 -1.1 microns is required for Earth imaging. This has significant implications for the technology development program as will be discussed in section §5.

Both PIAA and VV at 2λ/D are less mature and pose more risk than BL at 4λ/D, although on going efforts are showing promise. Nonetheless all, including the BL, need further development to bring the technology up to TRL 6. It is very important to note that the maturation program for any of these coronagraph systems, including the wavefront sensing & control (WFSC) and deformable mirrors (DMs), is essentially the same for any of the mission scales proposed to the ASTRO2010, from large flagships at 8m to 1.5m probe class observatory designs.

For the purpose of costing, it has been shown that while the PIAA implementation is more complex than a Lyot architecture, the impact on mass and power is minimal compared to the overall needs of the observatory. Hence we suggest that the Coronagraph instrument table provided in the TPF-C RFI#2 (Table 6) remains applicable for the CSI in ***TPF-C 4m***.

3.2.3 Wide Field Camera

For the purpose of this RFI#2 we assume the same design for the Wide Field Camera (WFC) as for TPF-C FB1 [16]. However, should further studies be performed we would redesign the WFC as ***TPF-C***

4m provides more volume for the instrument module than does the FB1 configuration. Furthermore, the FB1 baseline design was developed without a wide field requirement and the telescope optical design was chosen to be a 2 mirror system. A wide field camera for general astrophysics was added late in the design process and was accommodated on a best effort basis without significantly changing the overall configuration or telescope design. Converting the telescope to a 3 mirror system was considered, in order to reduce aberrations over a wide field, but it was found that space was not available for this third optic for FB1. It is likely that a redesign of ***TPF-C 4m*** would incorporate a 3 mirror telescope. In FB1 the WFC was required to provide its own optical corrections. This is extremely difficult to accomplish within the limited volume allocation. For FB1, Ball Aerospace developed a quite ingenious solution to this challenge, but this by necessity required some compromise with image quality and field of view (FOV) [16]. These constraints would no longer apply to TPF-C 4m where the WFC and the Observatory would be designed concurrently and without major volume restrictions.

TPF-C 4m will likely be a Three Mirror Anastigmat (TMA) design and there will be ample volume for a WFC. A tertiary mirror could be included within the WFC and a separate tertiary in the coronagraph to allow a tailored focal length. An improved PSF, larger complement of filters and larger FOV is possible. A square FOV approaching 20 arc-minutes with a square pixel FOV less than 20 mas is viable.

3.3 SPACECRAFT

Overall, the spacecraft design for ***TPF-C 4m*** will remain essentially identical to the one proposed for TPF-C FB1. Variations to that design are discussed below.

3.3.1 Vibration Isolation

As mentioned previously, for ***TPF-C 4m*** we baseline a 2-stage passive vibration isolation. The first passive isolation stage is identical to that implemented on FB1 is located directly on the reaction wheel mounts as they are the largest expected disturbance on the spacecraft. A second passive isolation stage will be located at the interface of the spacecraft and the observatory to further dampen out any residual disturbances from the spacecraft. This is especially easy to implement since the ***TPF-C 4m*** design has well defined interfaces between the two distinct systems. The 2-stage passive vibration isolation method is very mature and poses little risk. Should analyses prove the 2-stage passive isolation to be marginal in achieving the required stability, then a viable off-ramp would be to implement active vibration control solutions. Several active isolation options exist and are at various stages of maturation; all pose higher risk and cost than the passive solution. Analyses performed on the larger more flexible TPF-C FB1 showed that wavefront jitter stability at $4\lambda/D$ was met comfortably with a single-layer passive vibration isolation system at the reaction wheel while an active system provided more than an order of magnitude of margin. Similarly the much smaller and stiffer PECO design met its jitter stability at $2\lambda/D$ with only single-stage passive isolation even though the specifications are 10 times tighter than for TPF-C FB1 at $4\lambda/D$, and active isolation provided more than an order of magnitude of magnitude of margin. Since TPF-C FB1 and PECO bound ***TPF-C 4m*** in stiffness and performance requirements we can assume that a 2-stage vibration isolation is a viable solution and that the order of magnitude of margin provided by the active vibration isolation system will be sufficient to meet the specifications as a fall back option. Of course more detailed analyses are required to verify this preliminary design assumption.

3.3.2 Thermal Control

The additional volume available for packaging the instruments behind the ***TPF-C 4m*** primary mirror makes it easier to provide a larger thermal cavity for isolation between the sensitive coronagraph and telescope components and other heat dissipating components. As for FB1, ***TPF-C 4m*** will have an actively controlled thermal cavity for radiative control stabilization of the primary mirror to near room temperature with milli Kelvin or better stability. As a reminder, TPF-C is allowed to have large gradients across and through the thickness of the PM, as long as the gradients remain extremely stable during the observation and in between resetting of the wavefront with the DMs. The main purpose of the actively controlled thermal cavity is to minimize the impact of thermal transients after a slew. While the thermal stability requirements are tighter on ***TPF-C 4m***, achieving those requirements is greatly facilitated by the removal of spacecraft rolls to complete an observation, as required for FB1.

In TPF-C FB1 the V-groove sunshade has to wrap all the way around the payload, to keep sun light from entering the V-grooves as the telescope is rolled through almost 120 degrees. This requires the v-groove sunshade to deploy around fixed thermal radiators for cooling instrument detectors; a significant complication to the deployment. For ***TPF-C 4m***, without multiple roll angles, a "dark side" can be maintained such that the V-groove sunshade can be open on that side, avoiding any interaction with the instrument thermal radiators.

Beyond the interference with the radiators, the V-groove sunshade on TPF-C FB1 has to be tightly packaged for launch to fit inside the shroud. Deployment of the sunshade required a complex unfurling sequence including telescoping ribs and a ring truss at the top of the structure to maintain membrane separation. On ***TPF-C 4m,*** the V-groove sunshade deployment will be greatly simplified as the ribs will just be fanned out from their base with spreader bars similar to JWST's that will simply lock them in place at the top to maintain separation. Not withstanding is the shear size difference between the V-groove sunshade system required to athermalize a 14m-long telescope and that required for an approximately 6m-long telescope such as ***TPF-C 4m***.. Over all, the design of the V-groove sunshade on ***TPF-C 4m*** is significantly less complex and poses much less risk than that required for the large flagship TPF-C FB1, with associated benefits in total mass and ground testing prior to launch. As a side note, this mass savings could be used to further stiffen the overall observatory and improve its stability.

3.3.3 Solar Sail

The TPF-C FB1 design includes a solar sail to balance the torque induced by solar pressure on the sunshade. Without a solar sail, observation times would be limited by reaction wheel capacity, with a current estimate of only 4 hours. Since the V-groove sunshade on ***TPF-C 4m*** will be about half the size of the one on TPF-C FB1, it is very likely that it would obviate the need for any solar sail at all, or at least one much smaller in size, further reducing mass, cost and risk to the mission.

3.4 CONFIGURATION

A stated objective for the TPF-C FB1 design study was to provide the largest possible aperture that can be launched with currently available launch vehicle (LV) fairings, the Delta-IV Heavy with a 5m diameter fairing. Packaging considerations ultimately resulted in launching the 8m x 3.5m FB1 PMA in

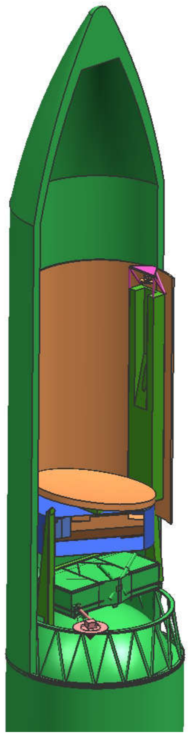

Figure 2 *TPF-C 4m* Schematic of the Stowed Configuration in DeltaIV-H

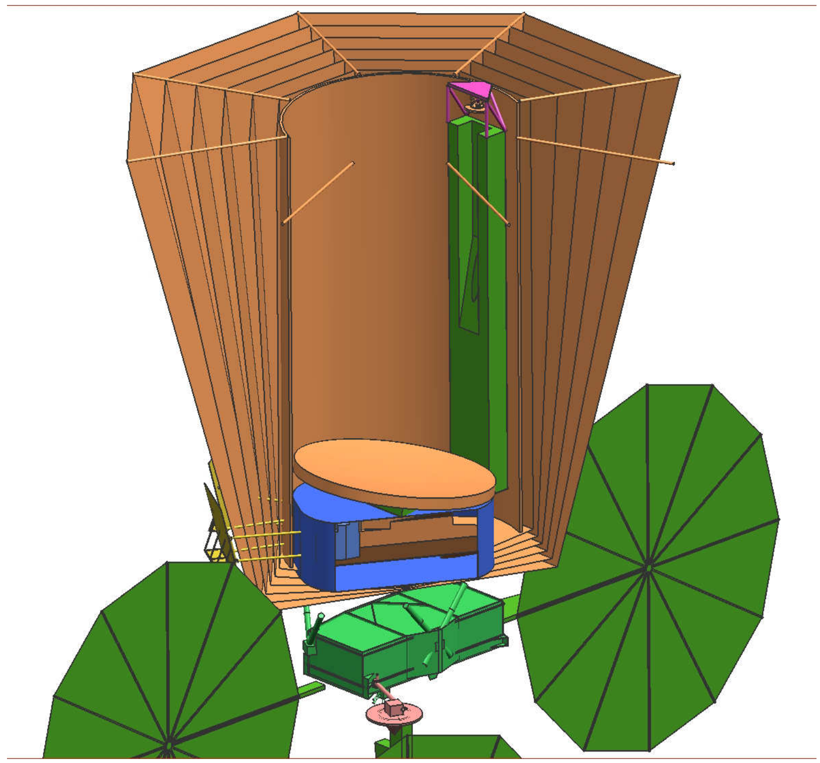

Figure 3 *TPF-C 4m* Schematic of the Deployed Configuration

a vertical position, leaving little space both in front and behind the primary mirror for the other sub-systems. Nonetheless a solution exists which requires complex deployments of the PMA, the secondary mirror tower, the V-groove sunshade as well as the payload adapters that are jettisoned after launch. The volume available for packaging the instruments is limited and the spacecraft bus equipment is wrapped around the instruments.

The ***TPF-C 4m*** configuration becomes more conventional with fewer and less complicated deployments. The telescope has a fixed secondary tower and a fixed outer barrel. The V-groove sunshade wraps around the outer barrel and deploys with only a radial motion. Structural loads are carried through the spacecraft bus structure with direct load paths and no jettisoned structure. The space available for instruments is large and the spacecraft bus stacks beneath the payload in a modular fashion with well defined and distinct interfaces which are used to further isolate any dynamic and thermal disturbances generated by the spacecraft. The stowed and deployed configurations for ***TPF-C 4m*** are shown in Figure 2 and Figure 3 respectively.

3.5 OTHER CONSIDERATIONS

The system level integration and test (I&T) activity is greatly simplified with ***TPF-C 4m***; the modular configuration adds schedule resiliency and the development of I&T facilities is easier.

Fabrication and processing of the ***TPF-C 4m*** primary mirror is easier (e.g., less facility development) quicker (less area) and less risky (less lightening, higher density).

4. ENABLING TECHNOLOGY

4.1 TECHNOLOGY READINESS OF THE MAJOR ELEMENTS

Table 3 below summarizes the technology readiness of the major ***TPF-C 4m***. It is reproduced from the TPF-C FB1 (Table 4 in RFI#2). Some of the TRLs have been changed because of the size, stability and deployment differences between the two architectures. Changes are identified in red font; all other estimates remain identical to TPF-C FB1.

Table 3 Technology Readiness Level of Major Elements

Technology Readiness Level of Major Elements			
Element	**Current TRL**	**Phase A Goal**	**Rationale**
Starlight Suppression			
System Performance Demonstration	3	5	The Lyot band-limited mask is the most mature coronagraph at TRL 4 having achieved < 10^{-9} contrast at $4\lambda/D$ in 10% bandwidth. The PIAA and VV coronagraphs options at $2\lambda/D$ are less mature. By the end of Phase A, system performance will be demonstrated w/ a full dark hole at < 10^{-9} contrast at $2\lambda/D$ in 10% bandwidth
Apodizing Masks and Stops	3-4	5	Masks used in conjunction w/ system performance demonstrations at required levels. Candidate masks have controlled fabrication and are well characterized.
Wavefront Sensing & Control	3-4	5	TRL consistent w/ system performance targets & dual-DM configuration
Deformable Mirrors	5	6	Performance goals achieved w/ 32x32mm DM units. 48x48mm DM system w/ cabling & electronics have been flight qualified. Develop 96x96mm in Phase A.
Small Precision Optics	4	5	Lab demonstrations are successful using small optics w/ SOA PSD surface roughness, material homogeneity, coatings. Need to quantify requirements for flight
Instrument Pointing Control	3	5+	Demonstrate within coronagraph open-loop control accuracy, resolution on FSM at 50HZ bandwidth and 1 mas measurement accuracy on FGS at 500Hz. An approach using a Low-Order Wavefront Sensor (Guyon, 2008) has already been successfully demonstrated to TPF-C levels.
Observatory Stability			
2-Stage Passive Vibration Isolation & Pointing	5	6+	Select 2-stage passive isolation design and test dynamic stability capability. Off-ramp with existing active isolation options such as the DFP from LM or the ITT Active Isolation Mount system
Observatory thermal control	4	6	Assess performance of subscale sunshield engineering unit (JWST) and of isothermal cavity on surrogate sub-scale PM. Correlate thermal models and apply to flight design.
Precision System Modeling			
Integrated Modeling Capability	3	5	Demonstrate ability to compute thermal, structural responses to the degree of accuracy required by TPF-C. Validate models against testbed results w/ increased level of sophistication in nonlinear heat transfer, active thermal/pointing control, nonlinear structural behavior, and

			non-uniform materials.
Large ~~Deployable~~ Space Optics			
Primary Mirror	**5**	5-6	Low Temperature Fusion (LTF) is used as the approach for joining hexagonal segments for PM fabrication. This technology has already been brought to a TRL 6 using a 1.4m AMSD like test article. Optics fabricated using this approach are accepted for flight based on visual inspection as well as on destructive testing of witness sample which are assembled in the same furnace cycles as the flight part, and no further technology development is required. Risk in LTF of a 4m mirror would be mitigated through analysis, which has been the approach used in the past.
Secondary Mirror Position Control	4	6	Build and test active hexapod w/ metrology system to demonstrate 6 DOF position control to a level of 15nm over 5 mm range. Within SOA capability. Components already exist and system architecture needs maturation.

4.2 THREE PRIMARY TECHNICAL RISKS

The three highest technical risks for ***TPF-C 4m*** are Starlight Suppression, Observatory Stability and Precision System Modeling, as summarized in Table 2.

Observatory Stability is the ***TPF-C 4m*** risk that has replaced "Large Deployable Optics" in TPF-C FB1. First this is because thermal and dynamic wavefront stability requirements become tighter at $2\lambda/D$ by a factor of 10. Furthermore there no longer are deployments in the telescope and the PM is half the size. Note that the wavefront stability requirements are independent of telescope size. Hence, the error budgets and performance verification analyses performed for the 1.4m PECO mission with a PIAA coronagraph are also applicable for a scaled up ***TPF-C 4m*** design. The PECO analyses performed on a detailed finite element model proved that the system was able to meet its jitter requirements with a passive vibration isolation system and its thermal stability with a passive thermal design. How these top level stability allocations are shared amongst the various sub-systems is design dependent and require detailed analyses of the engineering models. This has yet to be performed for ***TPF-C 4m***.

In order to achieve the jitter stability requirements we propose a baseline 2-stage passive vibration isolation at reaction wheel and spacecraft interfaces, respectively. Reaction wheels are expected to be the largest dynamic disturbance in the system. The Low Order Wave Front Sensor (LOWFS) within the coronagraph with bandwidths of 500Hz with further be used to ensure the instrument pointing requirement. Both would need to be matured to TRL 5 to TPF-C levels by the end of Phase A, although options for passive vibration RWA vibration control may already be at TRL 6. Furthermore while analyses show that TPF-C FB1 can achieve its performance without active vibration isolation, such technologies could be considered and used as an off-ramp for the purpose of providing better margin or relaxing other wavefront error contributors in the system.

Thermal stability on ***TPF-C 4m*** is achieved using the same thermal control architecture as on TPF-C FB1 with a 5-layer V-groove sunshade and an isothermal cavity behind the PM. Hence no changes are required from the plan formulated to mature thermal technologies on TPF-C FB1. Although the stability requirements are more challenging on ***TPF-C 4m***, this is offset by a stiffer and smaller observatory and a more stable observing strategy because of the circularity of the PM. Analyses are required to verify the system performance. Furthermore, the V-groove sunshade no longer requires a complex deployment scheme which alleviates a major part of the sub-system risk for the spacecraft.

Starlight Suppression is a common risk with TPF-C FB1 where the main difference is in the coronagraph design at 2λ/D. The VV shares the same instrument system architecture and optics as the BL coronagraph in FB1 and fabricating a VV mask to Earth detection levels is currently being matured. PIAA coronagraph is also being developed with the delivery of 2nd generation PIAA aspheric optics from Tinsley under contract from NASA ARC which are being tested at JPL in the precision High Contrast Imaging Testbed (HCIT). Both the VV and PIAA are estimated to be at TRL 3 compared to the BL at TRL 4, however we anticipate no road blocks to mature any of these technologies to TRL 6, given sufficient technology demonstration funding is provided.

All coronagraphs, either at 2λ/D or 4λ/D share the same technology needs for wavefront sensing and control (WFSC), nulling algorithms and deformable mirrors (DM). Achieving broadband performance (e.g., >10%) may be more challenging with a PIAA-type coronagraph, although all coronagraph approaches share dispersion and polarization problems and all are investigating wavefront control options with 2 DMs as mitigation approaches. It is also important to note that regardless of the coronagraph option or the size of the mission, the instrument can be tested full scale to Earth detection levels in existing facilities such as the High Contrast Imaging Testbed (HCIT) at JPL.

Precision System Modeling: ***TPF-C 4m*** will implement a "Verification by analysis" approach, as will any of the exoplanet imaging missions regardless of size. While facilities exist to test the ***TPF-C 4m*** full-scale, the ground environment, especially stability, will hamper the ability to demonstrate contrast performance end-to-end to earth detection levels. A challenge for ***TPF-C 4m*** will be to develop engineering analysis tools and models (integrated thermal-structures-optics) that can accurately predict temperature changes to milli Kelvins and wavefront changes from PM deformations in the 10's of picometer. As defined in the TPF-C FB1 technology plan, surrogate mirrors in conjunction with a sub-scale thermal control system will be tested extensively to demonstrate the predictive capability and uncertainties of the models. For ***TPF-C 4m*** the predictive accuracy will need to be about an order of magnitude tighter than for TPF-C FB1, although it is important to realize that the prediction is for relative changes in the temperature, pointing and wavefront as opposed to an absolute estimate for those parameters. To mitigate the risk, modeling uncertainties will be folded into the flight system error budget in the same manner as is traditionally done for fabrication tolerances and will be accounted for in the overall system verification. Furthermore, we will rely on the active and passive control systems to adjust for variations once on-orbit. The control systems available to adjust wavefront stability are the 2-stage vibration isolation, the SM 6 degree of freedom position and pointing control, the thermal control of isothermal cavity and of course the deformable mirrors and LOWFS within the coronagraph. It is only required that the models predict accurately to within the capture range and bandwidth of the multi-layer active control system and that the system have enough control authority to achieve the required precision.

4.3 TECHNOLOGY DEVELOPMENT PLAN

One very attractive feature of exoplanet missions using internal coronagraphs is that the overall technology development plan follows the same path regardless of mission size (probe to flagship) and has off-ramps along the way depending on mission scale and contrast goals. Such a plan is shown graphically in Figure 4

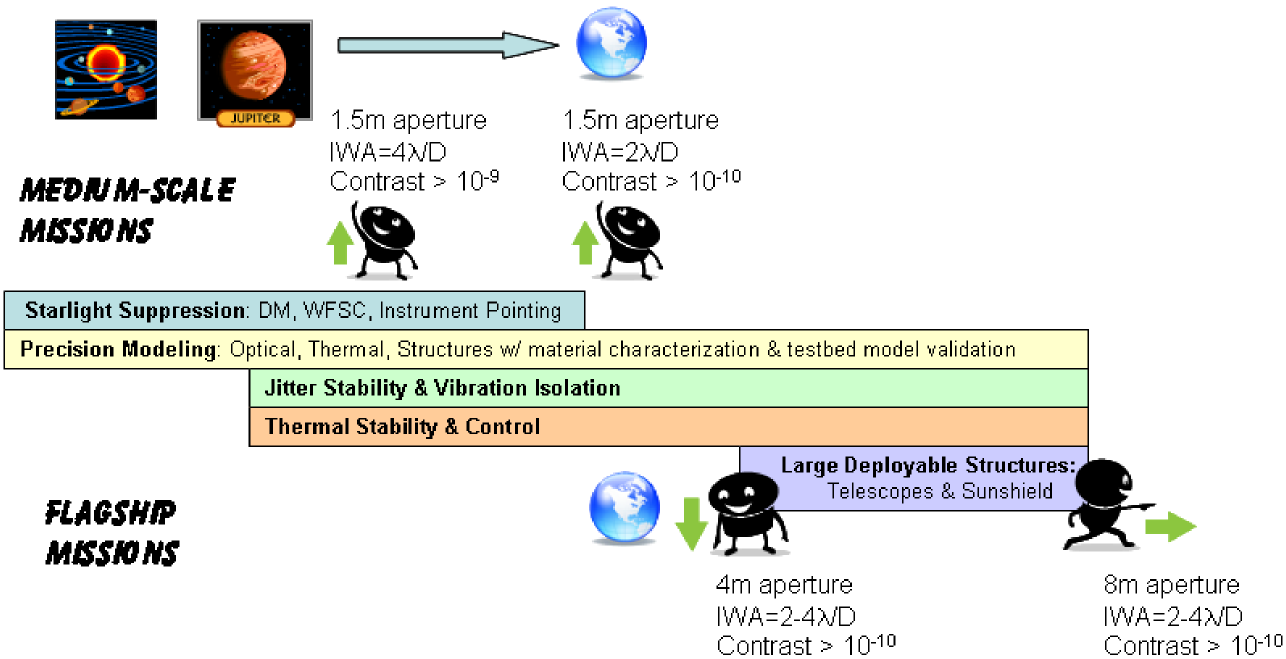

Figure 4 Exoplanet Mission Technology Development Approach with Off-Ramps as a Function of Mission Goals and Size.

Regardless of the mission scale, the technology maturation needs to start with the demonstration of the starlight suppression instrument with its coronagraphic mask, wavefront sensing and control and deformable mirrors. Demonstrating coronagraphs at 2λ/D to Earth imaging levels should be a priority as it will anchor the feasibility of more aggressive missions.

Modeling and simulation is a common thread across all exoplanet mission types, the complexity and accuracy of which increases with the tighter stability requirements and larger apertures Modeling tools need to be developed immediately so that they are available for developing error budgets and assessing performance for any of the missions These models will be validated either against actual flight hardware at the probe scale or on sub-scale test articles for larger missions. If thought through in advance, models validated on probe-scale missions could possibly serve as technology demonstrations for larger flagships. Similarly, jitter and thermal control are required for all missions, where the complexity is driven by stability and aperture size. Finally, technologies for large deployable structures will only be required for big flagship missions that cannot fit without complex deployments inside the LV shroud.

5. COST

We have not carried out a detailed costing effort for ***TPF-C 4m*** internal. For the purpose of costing a 4m observatory, we invite the ASTRO2010 to refer to other submitted exoplanet missions with 4m telescope such as THEIA (PI Spergel) and New Worlds Observer (NWO, PI Cash), noting that the main differences impacting cost is the telescope diffraction limit which is kept at 500nm for TPF-C and is baselined at 300nm for THEIA. Hence, the quality of the primary mirror optic is driven by the diffraction limit for the UV science and not by the starlight suppression requirements or the size of the mission. For ***TPF-C 4m*** the primary mirror is of Hubble Space Telescope (HST) quality, just as it is designed for TPF-C FB1. Compared to these other 4m telescope missions, ***TPF-C 4m*** will have additional costs to cover the tighter stability requirements. This mainly comes in the form of a 2-stage passive vibration isolation system and an integrated thermal management system comprised of multi-layer V-groove sunshade. The other main difference affecting the total cost of the mission is the choice of architectures which for ***TPF-C 4m*** is a high performance high stability internal coronagraph imbedded in the back end of the 4m telescope as opposed to an external occulter approach advocated by THEIA and NWO which uses a similar 4m observatory but with the additional expense of a completely separate free flying occulter spacecraft to achieve the starlight suppression as opposed to an integrated coronagraph instrument for ***TPF-C 4m***.

Overall, the cost for a ***TPF-C 4m*** will be bracketed between a probe-scale (1.5m) concept such as ACCESS (PI Trauger) and PECO (PI Guyon) and the larger flagship TPF-C FB1 (PI Levine). It can also be assumed for now that the instrument suite described in the companion RFI#2 for TPF-C FB1 remains applicable for ***TPF-C 4m***, although the smaller telescope offers more volume for instruments and opens the possibility to alternate options, such as those advocated by other exoplanet missions with 4m observatories.

6. SUMMARY AND CONCLUSIONS

Table 3 summarizes the advantages and disadvantages for TPF-C 4m relative to TPF-C FB1

Table 3 Advantages and Disadvantages of a 4m TPF-C

Advantages	Disadvantages	Mitigating Factors
Reduced cost (partial as function of aperture)	Tighter backend instrument pointing increases cost and risk	Active isolation, large mass margin PECO demonstrates a high rate WF sensor
Reduced mass (large margin with Delta-IVH LV)	Tighter WF stability due to optic deformation	2-Stage passive isolation, w/ active options as fall back, large mass margin
Increased coronagraph throughput	Reduced coronagraph technology maturity	Multiple options- PIAA and vector vortex
Reduced search mode time (single roll angle)	Increased characterization time	Net effect on total mission performance is not clear Could extend mission life to make up for longer observing time w/ Δcost much less than alternative of a larger flagship mission
Reduced deployment complexity and number		
Simplified thermal shroud deployment and more stable environment		
Reduced PM processing time (area) and risk (density)		
Improved wide field correction with TMA design		
Improved wide field camera (PSF, FOV)		
Improved integration schedule resiliency (modular)		
Smaller solar sail or possibly none at all		
Improved stray-light rejection (fixed OBA)		
Technology development path follows that of smaller and larger coronagraph missions, with off-ramps depending on science goals		

A coronagraph operating at 2λ/D with a 4m circular aperture is a very attractive option with many advantages. The primary disadvantage is that backend pointing and certain wavefront stability specifications become tighter by a factor of 10. The application of 2-stage passive isolation is likely to provide a viable solution to these tighter specifications without major risk. However, a detailed study and analysis effort is needed to reach this conclusion with confidence.

We seek the support of the ASTRO2010 to recommend continued study of this very promising design.

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