System design and technology development for the Terrestrial Planet Finder infrared interferometer

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ABSTRACT

This paper describes the technical program that will demonstrate the viability of two mid-infrared interferometer architectures being developed for the Terrestrial Planet Finder (TPF) to support a mission concept downselect in 2006. The TPF science objectives are to survey a statistically significant number of nearby solar-type stars for radiation from terrestrial planets, to characterize these planets and to then perform spectroscopy for detection of biomarkers. A 4-telescope, 36-m Structurally-Connected Interferometer using a dual-chopped Bracewell nuller will meet the minimum science requirement to completely survey 30 nearby stars and partially survey 120 others. A Formation-Flying Interferometer will meet the full science requirement to completely survey 150 stars, and involves a trade between dual-chopped Bracewell, degenerate Angel Cross, and the Darwin bow-tie input pupil. The system engineering trades for the connected structure and formation-flying architectures are described. The top technical concerns for these architectures are mapped to technology developments that will retire these concerns prior to the project downselect between a mid-infrared nulling interferometer and a visible coronagraph.

Keywords: interferometry, terrestrial planets, nulling, formation-flying, cryogenic structures

1. INTRODUCTION

The goals of the Terrestrial Planet Finder (TPF) are to detect and characterize terrestrial-sized planets around nearby stars for signs of habitability and for evidence of life. The TPF science requirements are to survey a statistically meaningful number of solar-type stars for radiation from terrestrial planets, to characterize these planets and their orbital parameters, and to then perform follow-up spectroscopy on promising targets. In 2002, two mission concepts – a mid-infrared nulling interferometer and visible/near infrared coronagraph – were selected by the project as the most promising candidates for further pre-Phase A study leading to a mission concept downselect in 2006[1,2]. Science data at either the mid-IR or visible / near-IR wavelength ranges are expected to satisfy the project's science objectives[3]. For the mid-IR interferometer concept, two sub-architectures were recommended for study: a Structurally-Connected Interferometer (SCI) to meet the minimum TPF science requirement (a full survey of at least 30 stars, and partial survey of at least 120 others) and a Formation-Flying Interferometer (FFI) version to satisfy the full TPF science requirement (a full survey on all 150 stars).

Nulling interferometry and coronagraphy are two very different approaches to terrestrial planet detection, but both share the technical challenge of cancelling the bright diffraction pattern from a central star to permit detection of a relatively dim planet slightly (0.1 to 1.0 arcsec) off-axis[4]. The contrast ratio between planet and star is expected to be $\sim 10^{-6}$ in the mid IR and $\sim 10^{-10}$ at visible wavelengths. The basis for nulling interferometry is the combination of light from separate telescopes with the phase of one beam shifted by π radians, creating pattern on the sky of a central cancellation (null) and off-axis transmission. The null is centered on the star and the first transmission fringe (at an angle of $\sim\lambda/B$, where B is the baseline and λ is the center observing wavelength) is placed at the angular separation where a terrestrial planet might be. The transmission pattern is swept across possible planet orbit phases by rotating the collector array about the line of sight to the star. Using more than two collecting telescopes allows flexibility in the shaping the null and the

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suppression of background signal and instrumental instabilities via phase chopping. In a coronagraph, diffracted light from the central star is attenuated using apodizing pupil masks and coronagraphic stops, and scattered light is controlled using deformable mirrors[5]. Among the factors important to the mission concept downselect between the interferometer and coronagraph options will be the predicted (and desired) science throughput, predicted life-cycle cost, technology maturity, and perceived risk of implementation and operation.

The context for the current mission studies is the 2001 report by the National Research Council[6] which recommended a new major initiative in this decade for a TPF mission based on an infrared FFI architecture. This recommendation was preceded by a decade's worth of studies culminating in the 1999 TPF Book[7], a report by the TPF Science Working Group, which described a 5-year mission consisting of four 3.5m telescopes in a linear array of free-flyer spacecraft along with a fifth combining spacecraft in a 1 AU orbit (Earth-trailing or L2). In parallel, ESA proposed the IRSI (now Darwin) mission[8] to meet similar terrestrial planet finding goals, consisting of six 1.5m telescopes and a combiner instrument on a 2-dimensional array of free-flyers at L2. Since the National Research Council report, a broad industry trade study[9] considered ~80 alternative mission concepts from which the project recommended a ~40m SCI concept and an ~8-10m visible coronagraph for further study as possible alternatives to the FFI concept. Figs. 1 and 2 illustrate the two interferometer architectures under study.

TPF is managed by the Office of Space Science (OSS) Astronomy and Physics Division at NASA Headquarters. NASA has delegated the responsibility for pre-formulation study activities, technology development, formulation and implementation of the TPF mission to the Jet Propulsion Laboratory (JPL). TPF is managed as a pre-project study in the Origins and Fundamental Physics program office at JPL, which is part of the Astronomy and Physics Directorate at the Laboratory. Within the TPF project, the Interferometer System is accountable for delivering interferometry mission designs validated by technology results. A system architect leads top-level instrument trades and develops error budgets that tie project science goals to engineering requirements on the instrument and flight systems. The architect maintains a list of top technical concerns requiring mitigation prior to the downselect; these concerns are retired through a combination of system design and technology development[10]. The design team delivers mission designs that satisfy the error budget and also delivers an end-to-end simulation. The technology teams deliver validated models of testbed and component results which can be extended to the expected flight environments and flight requirements.

Pre-Phase A work on TPF involves a wide community. Engineers and scientists at JPL work closely with the TPF Science Working Group (SWG), consisting of leaders in the field from academia, industry, JPL and other NASA centers The Goddard Space Flight Center will participate in the Interferometer System design team, as will members of industry, to help create the strongest possible mission concepts. In addition, the JPL Interferometer System is conducting coordinated studies with ESA on a common infrared nulling architecture for TPF. Both industry and academia will participate in technology development through competitive proposals.

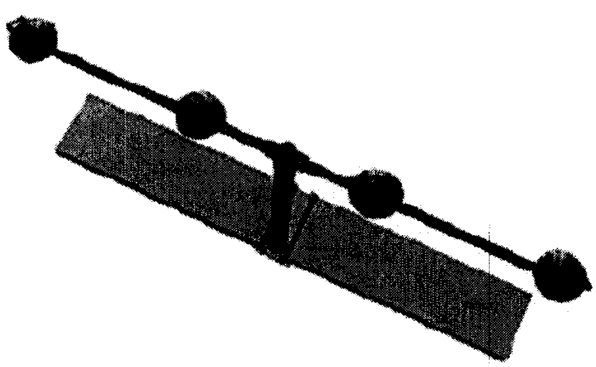

Fig. 1: A 40-m structurally-connected interferometer (SCI) configuration with four 3.5m diameter collectors (courtesy Lockheed Martin Space Corporation)

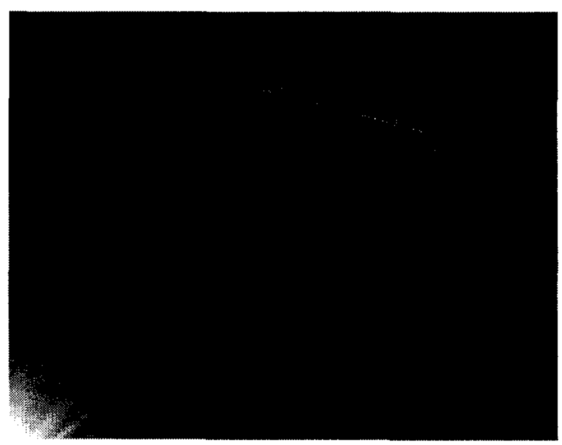

Fig. 2: A formation-flying interferometer (FFI) configuration with four 3.5m collectors and a combining spacecraft.

2. PROJECT SCIENCE

While the goal of TPF is to detect and characterize terrestrial-sized planets around nearby stars, this general statement requires greater specificity to arrive at an instrument matched to the goal. The TPF SWG is currently developing a set of specific scientific drivers including which set of stars (and how many such stars) TPF needs to survey, how close to the star TPF must observe, and how small the smallest detectable planet should be. The interim science requirements, which are not finalized, are briefly summarized below. The major difference in science requirements between the interferometer and coronagraph architectures is the observing waveband: for the interferometer the desired waveband is in the mid infrared (6.5 – 17 μm) whereas the coronagraph waveband is in the visible / near infrared (0.5 to 1.1 μm).

Engineering constraints on array size and collecting apertures limit angular resolution and sensitivity, restricting TPF to a survey of nearby stars. Unfortunately, we know relatively little about planetary systems around these stars. Using transit detections the Kepler mission is expected to yield statistics on the frequency of terrestrial planets in the galaxy but not survey TPF target stars. The Space Interferometry Mission (SIM) will survey TPF target stars and will detect jovian and terrestrial planets by indirect astrometric methods. Until then, the TPF science requirements are based on decreasing the probability of a false negative result to an acceptably small level. The minimum science requirements are that TPF must be able to fully observe at least 30 late-F, G and K main sequence stars, and to partially observe another sample of 120 such stars. The full science requires a complete survey for the entire sample of 150 stars.

The target stars are thus not too distant in type from our own G2 star. Of course, the total number of target stars desired sets the maximum distance to which TPF needs to be able to observe (especially after eliminating candidate stars for reasons of e.g. binarity, high exozodiacal dust content, etc.), and so sets the size of interferometer (angular resolution criterion), as well as the sizes of the individual telescopes (sensitivity criterion). There is also a strong scientific desire for a reasonably large field of view, 0.5-1 arcsec, both to search the nearest stars for terrestrial planets and to characterize giant planets in a subset of the stars. Although there are relatively few stars very close to us, the nearest few have sentimental value, and so the nearest stars are presently prominent on the interesting target list. The ability to observe stars both near and far will be one of the discriminators among the various architectures and configurations.

A single observation (consisting of a full interferometer revolution about the line of sight to the star) will typically not suffice either to convincingly detect very faint planets, or to definitively rule out their existence in a given star's habitable zone. Thus a small number (of order 3) of repeat visits will need to occur within the initial survey period, in order to confirm existences, to allow observations of different regions of the system's orbital parameter space, or alternatively, to rule out with high probability the existence of terrestrial planets in a given star's continuously habitable zone (CHZ). Because the interesting regions are likely to be near the inner angular resolution limit of either instrument, the detection/rejection goals need be expressed, as in the draft SWG science requirements statement, in probabilistic terminology. To paraphrase from the current draft[11], "within the CHZ defined by 0.9-1.1 AU for a G-type star, TPF shall be able to detect with 95% completeness, terrestrial planets at least half the surface area of the Earth. Within a more generously defined HZ (0.7-1.5 AU for a G-dwarf), TPF shall be able to detect an Earth-sized planet with 95% completeness."

TPF must also be able to obtain spectra of detected planets, in an effort determine the existence or absence of an atmosphere, and, in the thermal infrared case, the presence of such molecules as water, carbon dioxide, ozone and methane if these are present in interesting quantities. The wavelength range being considered is 6.5 – 17 μm with a fallback to 6.5-13 μm. Only low resolution (resolving power, R = 25) is being considered in the infrared, except that for the brightest sources the goal is for the spectrometer to be capable of R>100.

The initial survey of the core stars is to be completed in two years. During the remainder of the 5 year mission, it is envisioned that additional time would be devoted to the more accurate determination of planetary orbits and to more extensive spectroscopic observations.

3. ARCHITECTURE STUDIES

This section describes the fundamental instrument architectures that respond to the science requirements. These instrument architectures provide a basis for deriving the top technical concerns to be retired before the mission concept downselect. How these concerns are retired is described in Sections 4 and 5.

3.1. Architecture Studies

The TPF Interferometer System architecture team is working with the TPF SWG to select baseline architectures for the minimum and full science missions. Table 1 summarizes features for the current configurations – one for the minimum science mission, and an open trade between four options for the full science mission. Array size is defined as the distance between the outermost collectors in a given array, measured from the center of the optic. Table 2 lists key parameters in the analysis used to generate the configurations of Table 1. The inner distance that the interferometer can detect a planet is assumed to be the peak of the first fringe. This peak is placed a factor of 1.29 inside the inner habitable zone in order to provide 95% completeness for 3 visits assuming a distribution of target orbital inclinations.

We have considered a large number of entrance pupil configurations[12], for example Bracewell, dual-Bracewell, Degenerate Angel Cross, Angel Cross, OASES, Darwin Laurance, Darwin bow-tie, etc and at this time have narrowed our selection range by placing the following requirements on the configurations:

i) exo-zodi suppression (implies asymmetric response on the sky)
ii) instrument background suppression (implies chopping)
iii) feasible beam combiner

Table 1: Configuration Summary

Design Feature	Minimum Science Mission	Full Science Mission			
		(A)	(B)	(C)	(D)
Platform	Connected Structure	Formation-flying	Formation-flying	Formation-flying	Formation-flying
Input pupil	Dual Bracewell	Dual Bracewell	Degenerate Angel Cross	Darwin 2-D bow-tie	Darwin 2-D bow-tie
Phase Chopping	Yes	Yes	Yes	Yes	Yes
Array size[a]	36m	70m	70m	55m	55m
Collecting Area	4 x 3.2m diameter apertures	4 x 3.0m diameter apertures	4 x 3.0m diameter apertures	6 x 2.0m diameter apertures	6 x 2.5m diameter apertures
No. of Launches	1	1	1	1	2
Instantaneous Sky Coverage (from anti sun)	+/- 45 degrees	+/- 45 degrees	+/- 45 degrees	+/- 45 degrees	+/- 45 degrees

[a] Defined as distance between outermost collectors, measured from center of optic

Table 2: Key Parameters Used in Trade Analysis

Parameter	Value
Inner Habitable Zone / Inner Working Distance	1.29
Inner Habitable Zone / Mid Habitable Zone	0.7
Number of visits on each star	3
SNR for Detection	5
Peak of First Fringe / Inner Working Distance	1

The entrance pupil configurations that are still being considered are shown in Fig. 3. The key figure of merits for the choice of architectures are i) total number of observable stars and ii) number of observable nearby stars (< 5 parsec).

To observe a large number of stars the interferometer must have the resolution to look at the stars further away and yet have the null width sufficient to suppress the stellar leakage when observing nearby stars. The resolution and null width are inversely proportional to each other and scale with array size for a given design. The longer the array size, the separation between the centers of the outmost collectors, the better the resolution and narrower the null width of the interferometer.

For SCI resolution is the key limiting parameter, because the array size is restricted by how long of a structure can be deployed in space. Consequently we chose Dual Bracewell entrance pupil, because, of all the chopping capable entrance pupils, it has the highest angular resolution for a given array length. Table 1 lists consistent parameters which will enable the SCI to meet the minimum science requirements.

Sensitivity is the limiting parameter for the FFI configurations, since resolution is not an issue as one can increase the array size almost arbitrarily. To observe the nearby stars with longer minimum array size, it is beneficial for the interferometer to have a broader null than that of the Dual Bracewell (θ^2 null). Consequently we are looking at two θ^4 entrance pupil options: linear Degenerate Angel Cross with phase chopping and two-dimensional Darwin bow-tie array, currently baselined by the European Space Agency for the Darwin mission. Both of these provide broad enough nulls and are compatible with chopping. A Dual Bracewell has higher sensitivity than the θ^4 configurations and is shown for comparison. We have excluded OASES configurations from consideration because the broad θ^6 nulls do not offer any performance improvements over the θ^4 entrance pupils and yet make phase chopping very complicated. Array size was chosen to provide 20m between the edges of ~12m sunshields.

Another key parameter that impacts the number of observable stars is the total aperture collecting area. It determines the number of detected planet photons and is directly related to the integration time needed to observe a planet with a sufficient Signal-to-Noise Ratio. For the minimum science mission we are baselining four 3.2 meter apertures, while for the full science mission based on the FFI architecture we are in the process of investigating the aperture sizes of multiple spacecraft compatible with the available launch vehicles.

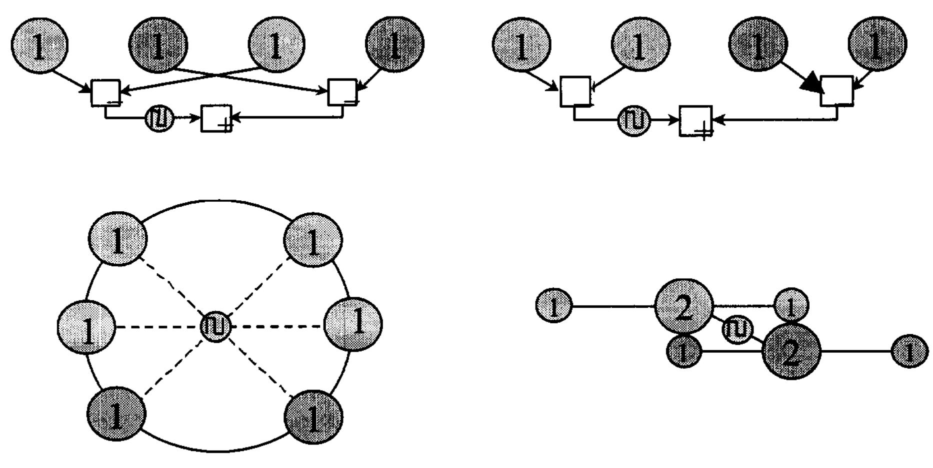

Fig. 3. Entrance pupil configurations for a) Dual Bracewell, high-resolutions and low-resolution, b) Degenerate Angel Cross, c) Darwin bow-tie. Number in circles refer to relative collective areas.

3.2. Top Technical Concerns

A flight implementation of any of the interferometer architectures summarized in Table 1 will represent a significant extension of current capability. The Interferometry Performance Model (IPM), a thorough error budget that ties the mission science requirements to instrument and flight system engineering requirements, was used to quantify the technical requirements for the TPF flight mission. In order to focus limited resources on the most critical system design and technology tasks, Kepner-Trego methods[13] were followed to qualitatively prioritize the technical concerns raised for the SCI and FFI architectures. Each concern was broken down into technical specifications that could be examined using the IPM. The TPF flight specifications were compared to current capability to establish the degree of technical gap.

Kepner-Trego methods suggest that concerns be prioritized not only by gap (seriousness) but also by urgency and the trend of the concern. Urgency for each concern or specification was based on whether the concern needed to be retired prior to the 2006 architecture decision or risk being a showstopper (high concern) or whether the concern could be retired during Phase A/B ending in 2011 (medium or low concern). Trend for each concern was tied to inheritance: if a technical concern is expected to be mitigated by work on another program, or will be demonstrated in a planned flight mission, then the trend priority would be lowered. Factors important to this assessment are timing of the planned inheritance relative to the TPF mission downselect, the confidence in the plan, and the degree of inheritance (general, evolutionary, or direct).

Table 3 lists those concerns whose priority was judged to be high or very high after considering technical gap, urgency, and trend. There are clearly more concerns than are listed in table 3 that must be addressed in the course of pre-Phase A and Phase A mission studies; however, these top technical concerns are the basis for what must be addressed prior to the mission downselect. The results of the process were vetted with the Navigator Independent Review Team and with the TPF Science Working Group.

There are several items not considered top technical concerns due to past or expected inheritance (trend). Picometer-level metrology will be demonstrated by the SIM mission. Interspacecraft nanometer-level metrology was developed in the StarLight technology program, and absolute metrology is being developed y by the Code R Distributged Spacecraft Technology program. Large infrared optics, mid-infrared detectors, and technology for passive cooling to 40K will be inherited from the James Webb Space Telescope. Interferometric nulling technologies are at the top of the concerns list. We continue to seek flight opportunities for demonstration of these technologies. With the cancellation of the StarLight mission, the technologies associated with precision formation-flying, algorithms, sensing, and system robustness remain remain as concerns requiring mitigation through the ground technology program and system engineering design.

Table 3: Top Technical Concerns for Interferometer Architectures

Category	Primary Concern	TPF Requirement	Current Capability	Primary Miti-gation[a]
Starlight Nulling Beamtrain	Nulling architecture	Survey 30-150 stars for terrestrial planets	Measure exozodiacal dust of nearby stars (Keck)	SE, A, B
	Beam combination	4 or 6 beams, 10^{-5} null 6.5-17μm	2 beams, 10^{-4} null 10-12 μm	A, B
	Internal thermal emissions	<<100 photons/sec	Immature (for ground IR interferometers)	SE
	Spatial Filters	70% throughput in single mode, 6.5-17μm	20% throughput 7-10 μm	C, A, B
	Intensity matching	0.2%	1%	F,A,B,G
	Phase control	1 nm (all frequencies)	10 nm (SIM)	A, B, F, G
Instrument Controls	Pointing control acc.of compressed beam	50 mas	400 mas	SE, O
	Cryogenic delay line closed loop stability	0.1 nm at 40K	<5 nm at 300 K	D
Detectors	Cryocoolers	30mW at 6K	0.5W at 30K	ACTDP[b]
Formation Flying System	Long-term system robustness	5-10 years	Untested	J, L, M
	Performance of fine formation control	1 cm range, 20 asec bearing accuracy	5 cm, 5 arcmin 2 s/c simulation	J, L
	Algorithm functionality in deep space	5 s/c autonomous sensing, collision avoidance, performance	2 s/c simulation	J, L, M
	Coarse acquisition sensor	50 cm, 1 deg, 4π sterarian FOV with no calibration maneuvers	50 cm, 30 deg, 1.3π steradian FOV (no calib maneuvers, 20 arcmin with calib maneuvers)	K, N
Formation-Flying Accommodation	RF interference from thermal shield	Low multipath effects on RF range measurements	Significant multipath effects on RF range measurements	K, N
	Interspacecraft stray light	<<100 photons/sec	Immature	SE
Precision Cryogenic Deployed Structures	Stability of long cryogenic structure	1nm / 36m / 40K	5nm / 5m / 300K	H, I
	Cryo hinge and latch stability	< 100 nm	0.1 to 10 μm	H, I
	Structural modeling tools	Confident prediction of performance	Limited cryo-nano models, not validated	H, I
Flight & Mission System	Launch packaging of structure and formation flight systems	Self imposed	4 x 3.2m diameter mirrors on sep s/c or 36-m structure	SE
	Interspacecraft communications	Continuous reliable high data rate 4 Mbits/sec	Immature	SE
	Sky coverage	At least +/- 45 deg	+/- 45 deg	SE
Integration and Performance Verification	End to end flight system test	Ability to verify multi-collector distributed flight system	Verification of large monolithic telescopes	SE, H
	Overall system complexity	Acceptable risk	Perceived as complex	SE,H,B, O,J,L, M
	Pseudo solar system	Simulate star and planet with 10^{-6} contrast 6.5-17μm over 0.1 – 1 arcsec	Artificial star systems	B

(a) SE = System Engineering; A, B, C, refers to Tables 5, 6, 7
(b) Advanced Cryocooler Technology Development Program

4. FLIGHT DESIGN STUDIES

To succeed in 2006 the design team must produce a design of a SCI and a design of a FFI representing credible solutions of what are acknowledged today as unsolved engineering challenges. Equally important are estimates for each design of end-to-end performance illustrating the proposed design has a good chance of meeting the requirements for a reasonable cost. This work complements, and takes advantage of, concurrent technology development described in Section 5.

To identify credible designs the TPF-I design team started by reviewing the very valuable work of others who preceeded us. Among other literature, we reviewed the TPF Book, ESA Darwin study and studies conducted in 2001-2002 by industry teams from Lockheed Martin, TRW (now Northrop Grumman), Ball Aerospace, and Boeing.

The next step for the JPL team was defining the trade space we intend to explore. We identified trades for over 80 features. This year's efforts focus on system-level sizing studies in preparation for next year's analyses of system performance and subsystem technology options. Table 4 summarizes recent and near term trade activities.

An L2 halo orbit was tentatively selected as a baseline over several options because of its low launch energy, consistent communications geometry, and the opportunity it provides for launch of a spare spacecraft should a previously deployed spacecraft of a constellation fail. Future study of the propulsion stage required to insert the interferometer into a halo orbit may suggest a reconsideration of an Earth trailing orbit.

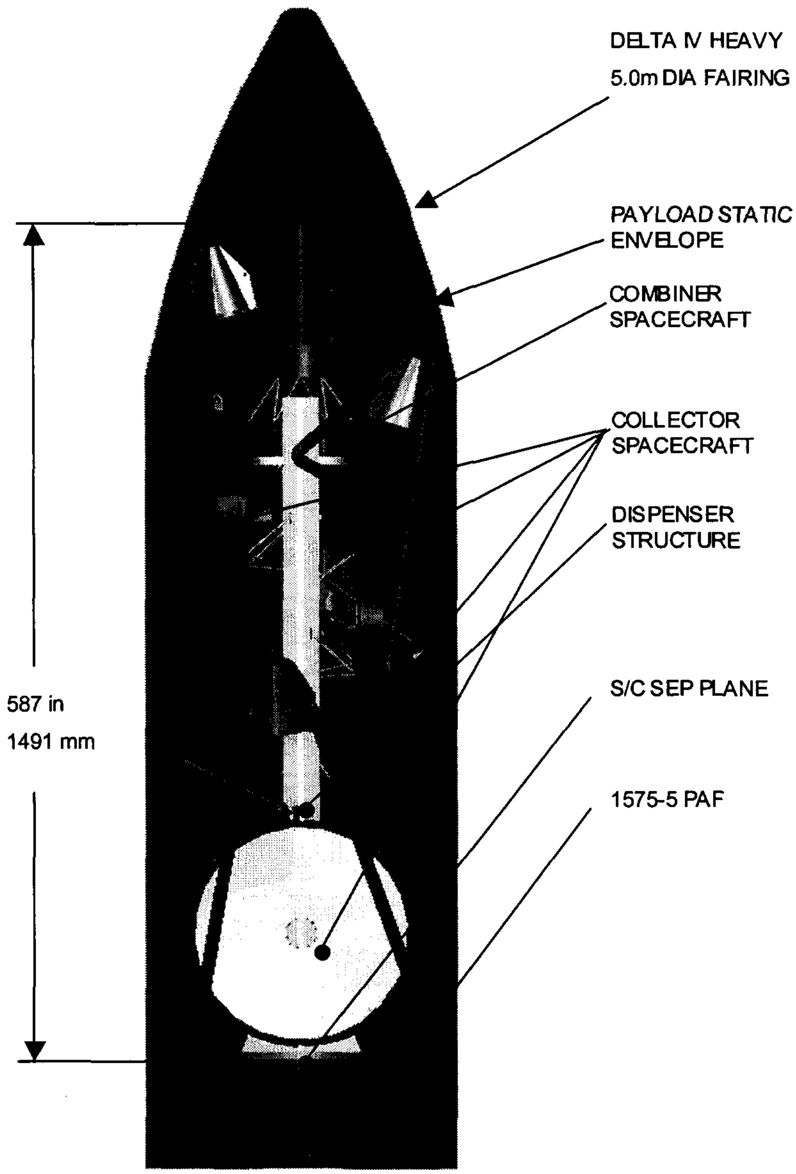

Fig. 4 Packaging of 4-collector, one combiner FFI into 19.1m fairing for Delta IV Heavy launch vehicle

The Delta IV Heavy launch vehicle was baselined because it is the largest U.S. vehicle currently planned for production. The working assumption is that a fairing as long as a previously advertised 22.4 meter x 5 meter option will be available before 2015. After choosing an L2 orbit, launch vehicle, and fairing the team has focused on mechanical configuration since these studies influence so many that follow. Launch packaging studies suggest primary mirror diameters of from 3.0 to 3.5 meters are feasible for either a FFI concept (Fig xx) of four apertures or a SCI concept of array lengths of 40 to 50 meters. This is consistent with earlier findings by the industry study teams.

Solar power was selected over radioisotope power because of cost and because the mission appears feasible without the use of radioisotope power. Radioisotope power was considered as part of orbit and architecture trades that would have portions of the flight systems shadowed (e.g. at L2, or free flying sunshield) or distant from the sun (e.g. at 5 AU).

Interferometers by their nature are highly integrated systems that are susceptible to small disturbances. As such, predictions of system performance rely on extensive modeling. Also, the TPF interferometer is too large to test as a complete system before launch. Consequently, software models of the system are a critical part of system design and verification. Recognizing this, a diverse program of modeling is already underway.

The team is starting with traditional stand-alone models such as thermal models, structural models, and optical models. With time the team will have integrated models. An early thrust named "Integrated Modeling of Optical Systems" (IMOS) is to develop a software translator that allows data interchange between these stand-alone models. Outputs of IMOS are then fed to the Observatory Simulation (ObSim) model. ObSim is an attempt to model the performance of the system from the sources of photons to delivery of science data. Other models are also in work including a Project Trades Model based on work at the Massachusetts Institute of Technology Space Systems Lab that attempts to capture the three key dimensions of cost, risk, and performance in one place.

The approach to attaining a reasonable cost for TPF is for the design team to consider cost as a dimension of each trade study. Currently, emphasis is being placed on the relative costs and cost uncertainties of design options rather than absolute costs. Cost is not being treated as an end in itself. The design team is sensitive to the importance of value and will be interacting with the project's Science Working Group on a regular basis to trade thoughts about the combination of cost and science return that forms value. The team's plan is not to present a solution but a set of options along the way for the SWG to consider.

Table 4:. Trades under study by the Design Team

Feature	Options	Status
Mission Design		
Orbit	L2, Earth trailing, 3 AU, 5 AU, Earth inclined, distant retrograde	L2
Launch vehicle	Single Delta IV Heavy, Single Atlas 5, Single Ariane 5, multiple launches of smaller LV's	Delta IV Heavy
Launch vehicle fairing	22.4 m, 19.8 m, 19.1 m	22.4 m
Spacecraft Design		
Power source	Solar arrays, radioisotope	Solar arrays
Coarse formation acquisition sensor	RF, optical, others	RF
SCI mechanical configuration	2-fold telescoping beams, 6-fold nontelescoping beams	In work
FFI mechanical configuration	4, 5, 6 aperture, various orientations of apertures in launch vehicle fairing	In work
Sunshield configuration & deployment	JWST-like, wraparound, free flying	In work
Fine pointing control technology	Colloid, FEEP, reaction wheels, others	In work
Spacecraft intercommunications	Dedicated UHF link, Shared RF link with	In work

	acquisition sensor, others	
Timing of formation or boom deployment	After launch, after orbit insertion	Planned
Other subsystem	Many	Planned
Instrument Design		
Telescope optical design	Secondary mirror on/off axis, various focal lengths	Planned
Position of tertiary mirror	Above primary, below primary	Planned
Metrology beam sensor	Quad cell, camera, others	Planned
Instrument detector technology	HgCdTe, SiAs, SiP, SiSb, SiGa, QWIP	Planned
Other instrument features	Many	Planned

5. TECHNOLOGY DEVELOPMENT

Technology development is planned for those top concerns not already addressed by system engineering inheritance. The technology areas are core interferometry, connected structure, and formation-flying, and are described below. Not described below is the Advanced Cyocooler Technology Development Program[14], managed separately at JPL, which is developing engineering model prototypes for JWST, Constellation-X and TPF capable of cooling to 6K.

5.1. Core Interferometry

Technology activities for core interferometry are recognized in table 5.
The **Achromatic Nulling Testbed** will be developed to address the optical issues related to achieving deep, broadband, dual-polarization, mid-infrared nulls. The testbed is based on the modified Mach Zender configuration. The list of technical issues and trades to be examined or developed includes field-flip vs. phase delay architectures, mid-infrared source characterization (lasers, filaments, etc.), symmetric beam injection approaches, planet injection approaches, intensity control devices, beamsplitter design, spatial filter evaluation, mid-infrared detector and camera selection, alignment algorithm development, and low-level null-control algorithm evaluation. The detection of off-axis sources will be demonstrated with a single baseline. The goal is to develop technology that will allow the TPF spectral band to be covered by only two nullers. The technical approach is to demonstrate performance of a cryo short wave (6.5–12 μm) nuller and to validate a model that will predict performance of a longwave (12-20 μm) nuller. The nuller schematic layout and photo of the breadboard optical system is shown in Fig. 5. Recently, a 10^{-6} laser null at 10 μm[15] has been demonstrated

Table 5: Technical Actvities for Core Interferometry

	Technology Activity	Description	Key Intended Result
A	Achromatic Nulling Testbed	Demonstrate two-beam mid-infrared nulling and off-axis source detection using representative star and planet photon fluxes.	• Stable 10^{-6} white light null with 50% bandwidth • 10^{-5} off-axis source detection
B	Phasing System Testbed	Address system complexity, system stabilization & noise suppression necessary to detect a planet	• Extraction of weak planet signal • (10^{-6} of star in white light) • Control of chopping to 0.1%
C	Mid Infrared Spatial Filter Technology	Single-mode mid-IR filters	• 50% throughput over 6.5^{-20} μm bandwidth
D	Cryogenic Delay Line	Three-stage opto/mechanical cryo mechanism	• Operate prototype closed-loop at 77K • 0.5 nm rms
E	Integrated Optics	Replace current bulk optics nullers with a set of integrated optics nullers	• Two-beam nuller, 5×10^{-5} null depth with 20% bandwidth at 10 μm.
F	Adaptive Nuller	Actively correct wavefront, intensity,	• Demonstrate 10^{-5} null with a

		and polarization	thermal 10 µm source, 40% bandwidth.
G	IR Optical Materials and Coatings	Optical materials & coatings meeting flight-like performance requirements.	• Components of broadband performance within 6.5 -17 µm range at cryo temperatures.

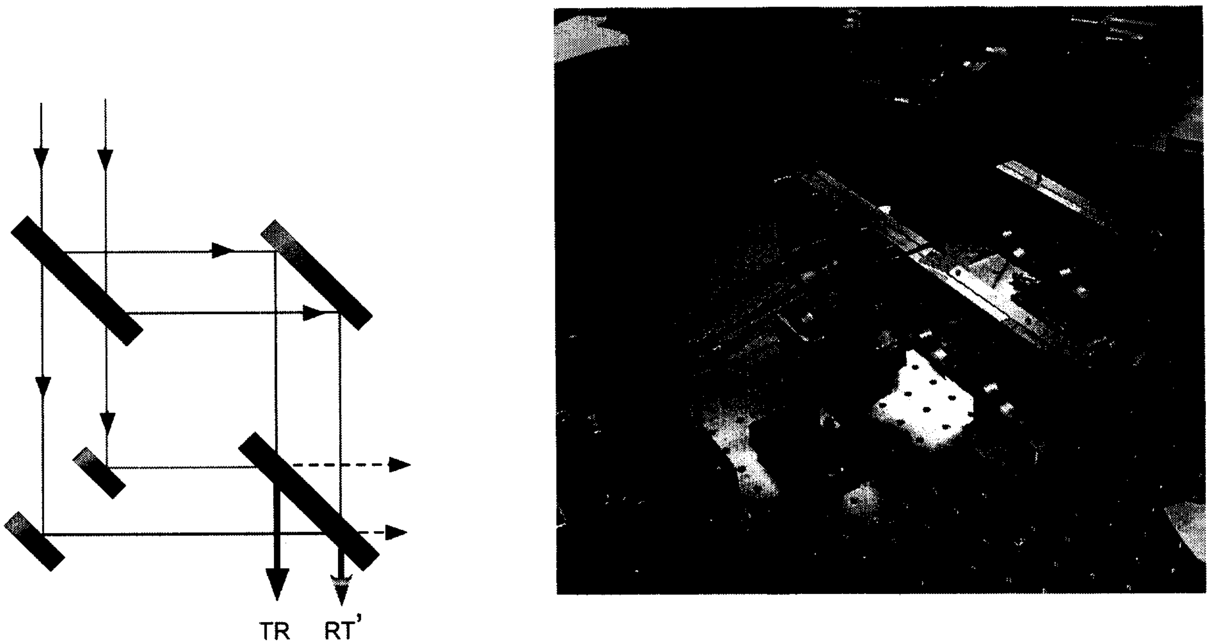

Figure 5: Schematic layout and view of the TPF mid-infrared Mach-Zehnder breadboard nuller

The **Phasing System Testbed** is an extension of the Achromatic Nulling Testbed and will address issues of system complexity and techniques for system stabilization and noise suppression necessary to detect a planet, based on a dual chopped Bracewell, modified Mach-Zehnder. The phasing system testbed will demonstrate the servo loops and control systems necessary for co-phasing of the four-input nulling interferometer. The emphasis will be on demonstration of instrument stability and noise suppression techniques (e.g., phase chopping needed to detect a planet). A combination of laser metrology and K-band fringe tracking will be developed for the pathlength control and knowledge. Fringe tracking and phasing of four starlight beams will be performed to a level of a few nm for white-light nulling. Translational motions of the separate telescopes will be simulated while fringe-tracking. Possibilities for demonstration of active and passive amplitude control are being investigated.

Spatial Filters Spatial filtering significantly reduces the optical aberrations in wavefronts, making extremely deep nulls possible. The most basic form of spatial filter used in infrared nulling up until now is a simple pinhole. The development of improved techniques for spatial filtering at mid-infrared wavelengths may be crucial to achieving broadband null depths of 10^{-6} Implementation options include single-mode fiber-optics made from halogenide polycrystals or chalcogenide glasses, waveguide structures micro-machined in silicon, or through the use of photonic crystal fibers.

The **Cryogenic Delay Line** provides the pathlength compensation that makes the measurement of interference fringes possible. When used for nulling interferometry, the delay line must control pathlengths so that the null is stable and controlled throughout the measurement. This activity will develop a low noise, low disturbance, high bandwidth optical delay line capable of sub-nanometer residual pathlength control requirements at cryogenic temperatures.

The object of the **Adaptive Nuller**[16] is to experimentally demonstrate a device that enables significant relaxation of the nulling requirements on the TPF interferometer optical train. The concept will actively correct for wavefront, intensity, and polarization imperfections of the beam train entering the nuller.

IR Optical Material and Coatings will procure beamsplitter and optics materials and coatings from various industry and university sources that will enable one or two nullers to cover the entire observation spectrum while operating at cryogenic temperatures. In addition a symmetric beam splitter is to be developed which will allow replacement of the dual-beamsplitter modified Mach Zehnder approach with a single nuller beamsplitter.

An **Integrated Optics** task will develop prototype components replacing current bulk optics nullers with a set of integrated optics nullers. Integrated optics implementation would greatly reduce the weight, size and complexity of the nuller and would dramatically improve its stability.

Table 6: Technology activities for the structurally-connected flight system

	Technology Activity	Description	Key Intended Result
H	Interferometer Testbed	Cryo testbed of representative structural/mechanical components and systems	• Measurement of structural performance and thermal stability, jitter, damping, and component (e.g., hinge/latch) behavior at cryogenic temperatures. Nanometer precision over frequencies of 0-300 Hz.
I	Cryogenic Structures Modeling and Technology	Cryo structure hardware characterization & modeling.	• Models that accurately predict component & system-level performance of structurally-connected interferometer testbed.

5.2. Connected Structure

Table 6 lists technology activities for the structurally-connected flight system

The objective of the **Structurally-Connected Interferometer Testbed** is to provide valuable experimental information applicable to mid-IR nulling interferometers on large, spaceborne, cryogenic, deployed structures by characterization of their vibration response and thermal stability. Dynamic and thermal stability measurements at the nanometer level on structures scalable to 25 to 40 meters in length and at temperatures traceable to <40 K will improve our ability to predict performance of TPF-class structures. At a minimum, measurements of structures, of ten or more meters in length, will be made to determine or predict their structural vibration characteristics, temporal and thermal stability, jitter, damping, and component (e.g., hinge/latch) behavior at cryogenic temperatures. These measurements will be used to improve the modeling of even larger structures.

The stability and vibration characteristics of interferometer support structures must be shown to meet the requirements of nulling. The **Cryogenic Structures Modeling and Technology** task will provide accurate mechanical models for predicting the zero-g behavior of a structurally-connected interferometer at cryogenic temperatures. Component level testing will be performed to validate nonlinear models at cryogenic temperatures. System-level structural models will be validated where possible using experimental data provided by the Structurally-Connected Interferometer Testbed.

5.3. Formation-flying

The Formation-Flying Technology testbeds summarized in Table 7 are under development to establish the viability of the formation-flying interferometer (FFI) mission architecture for the TPF, while retiring and mitigating mission risk. The testbeds are complementary in addressing the technology concerns for the overall formation-flying system. These technologies extend the work performed on the StarLight technology program.[17]

The **Formation Algorithms & Simulation Testbed (FAST)** is a distributed real-time testbed implemented across multiple independent computational platforms for end-to-end simulation of the TPF formation-flying system. Fundamental algorithms will be developed for the five-spacecraft TPF mission based upon the two-spacecraft algorithms developed for StarLight. The algorithms will be demonstrated in the high-fidelity end-to-end simulation environment to the full TPF performance of 2 cm and 1 arc-minute accuracy in range and bearing control. Realistic mission scenarios will be demonstrated, including formation acquisition, formation calibration, formation maneuvering, re-configuration, and nominal observation. The simulation will be further exercised with system fault scenarios to verify the long-term robustness of formation-flying missions. Scenarios will include collision avoidance and evaporation of the spacecraft formation, and system-level potential failure (eg thrusters, sensor)

The **Formation Sensor Testbed (FST)** will provide hardware demonstration of the formation acquisition sensor, validating the requirement to provide an instantaneous 4π-steradian field-of-view coverage in relative and bearing angle determination among multiple spacecraft required for initial acquisition of the formation and for collision avoidance. Maximum range and bearing uncertainty will be 50 cm and 1 degree over the full coverage. The acquisition sensor is a radio frequency (RF) sensor, based upon the StarLight Autonomous Formation-Flying (AFF) Sensor.[18] This testbed will develop the new algorithms for multiple spacecraft operation, a passive radar mode for added robustness against collision avoidance, and to eliminate the need for time-consuming calibration maneuvers. RF-based performance within TPF-like structural environment and accommodation constraints will be evaluated. FST will also provide sensor models to be used in the FAST system simulation.

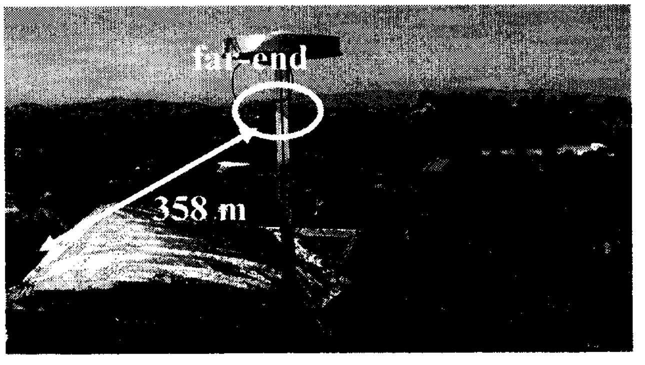

Fig. 6 The figure shows the prototype acquisition sensor operating across a 358-meter outdoor range to measure the relative distance and bearing.

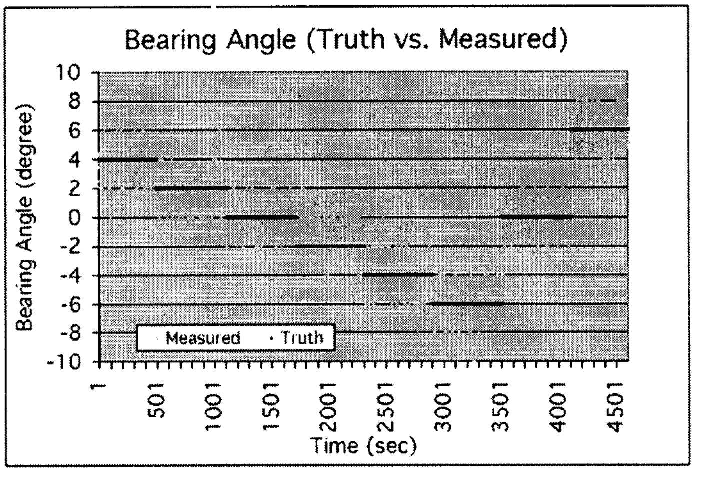

Figure 7: The figure shows results of the bearing angle measurement versus truth in shown for a scheme which will eliminate the need for relative spacecraft rotation for sensor calibration.

The **Formation Control Testbed (FCT)** will demonstrate end-to-end autonomous formation-flying in a 1-g environment with full TPF performance of 5 cm maximum uncertainty in range and 5 arc-minutes in bearing control accuracy. It will emulate real spacecraft dynamics using multiple mobile test vehicles equipped with flight-like avionic hardware and inter-spacecraft communication, moving on air-bearings. FCT will also provide validation of the FAST. FCT algorithms and prediction of FCT system performance will be developed in FAST. FCT system performance will be compared to the FAST predictions, and thus validating FAST modeling capability to predict TPF performance.

The Synchronized Position Hold Engage Re-orient Experimental Satellites **(SPHERES)** experiment[19] will perform TPF relevant maneuvers with three soccer-sized "spacecraft" in the International Space Station (ISS). Each SPHERE is self-contained with ultra-sonic relative sensors, ultrasonic global position sensing, thrusters and inter-spacecraft communication. The experiment will demonstrate functional feasibility of formation-flying over a 3m x 3m x 3m test area. It will provide lessons-learned for formation-flying.

The **Thermal Shield Testbed** will characterize the impact of different thermal shield materials on the RF sensor performance, inter-spacecraft straylight performance and thermal performance.

Table 7: Technology activities for formation-flying system

	Technology Activity	Description	Key Intended Result
J	Formation Algorithms and Simulation Testbed	Algorithm development and high-fidelity distributed real-time software testbed to demonstrate end-to-end TPF formation-flying system	• Demonstrate full TPF performance of 2 cm and 5 arcmin in range and bearing control
K	Formation Sensor Technology	Hardware development and demonstration of the formation acquisition sensor S-band	• Demonstrate range and bearing determination with 4π steradian field-of-view coverage with maximum uncertain of 50 cm and 1 degree in range and bearing
L	Formation Control Testbed	Ground-based laboratory for flight-like end-to-end demonstration using multiple mobile vehicles equipped with flight-like avionic hardware and air-bearing.	• Demonstrate end-to-end autonomous formation-flying in a 1-g environment with full TPF performance of 5 cm maximum uncertainty in range and 5 arcmin in bearing control accuracy
M	SPHERES Flight Experiments	Three soccer-sized "spacecraft" experiment to perform TPF representative maneuvers on the International Space Station	• Demonstrate functional feasibility of formation-flying in micro-g environment
N	Thermal Shield Technology	Thermal shield material selection and testing	• Select material acceptable for TPF based upon RF, thermal and optical performance
O	Formation Interferometer Testbed	An optical interferometer distributed over separate platforms representative of a formation-flying interferometer	• Demonstrate optical interferometer fringe acquisition and fringe tracking across two relatively moving platforms (30 μm/s)

6.0 SUMMARY

To be supplied by Gary.

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