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TECHNOLOGY AND DESIGN OF AN INFRARED INTERFEROMETER FOR THE TERRESTRIAL PLANET FINDER

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ABSTRACT

This paper describes the architecture studies, technology studies, and testbeds that demonstrate the viability of an infrared interferometer mission architecture for the Terrestrial Planet Finder project. A formation-flying and a structurally-connected architecture are discussed. Topics described are: past years' studies, relation of system performance requirements to science objectives, mission concept development and evaluation, formation-flying sensor and control testbeds, nulling interferometer technology development, and technology plans for cryogenic structures. Also described are how the planned technology and design activities retire the key technical concerns for the architecture concepts.

1. INTRODUCTION

Terrestrial Planet Finder is a NASA mission tentatively scheduled for launch in 2015. Its goal is to discover Earth-like planets orbiting in the continuously habitable zones around Sun-like stars and to characterize the atmospheres of those planets for evidence of life. The context for the current mission studies is the 2001 report by the National Research Council[1] which recommended a new major initiative in this decade for a TPF mission based on an infrared formation flying interferometer (FFI) architecture. This recommendation was preceded by a de*cade's worth of studies culminating in the 1999 TPF Book[2], a report by the TPF Science Working Group. The TPF Book describes a 5-year mission in an L2 or Earth-trailing orbit. The flight system consists of four 3.5m diameter telescopes in a linear array of free-flyer spacecraft along with a fifth combining spacecraft.

Since the National Research Council report, a broad industry trade study[3] generated ~80 alternative mission concepts from which the project recommended two for further study leading to a downselect planned for 2006. One alternative is a large coronagraph operating in the visible/near-IR spectrum. The other alternative is a mid-IR interferometer that has all collecting apertures and combiner mounted on a common structure. Two design and technology teams were formed. One team is studying the coronagraph concept. The other team is studying the FFI and structurally connected (SCI) interferometer concepts. This paper describes the efforts of the interferometer team.

Before delving further into the interferometer effort a few words are offered comparing the interferometer and coronagraph. Science data at either the mid-IR or visible /near-IR wavelength ranges are expected to completely satisfy the project's science objectives[4]. Nulling interferometry and coronagraphy are very different approaches to terrestrial planet detection, but both share the technical challenge of cancelling the bright diffraction pattern from a star to permit detection of a relatively dim planet 0.1 to 1.0 arcsec off-axis[5]. 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. This shift creates a pattern on the sky described by 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 locations by rotating the collector array about the line of sight to the star. By comparison, 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[6]. Among the factors important to the comparison in 2006 of the interferometer and coronagraph are the predicted science throughput, predicted life-cycle cost, technology maturity, and perceived risk of implementation and operation.

2. TEAM ORGANIZATION

The Office of Space Science Astronomy and Physics Division at NASA Headquarters manages TPF. The Jet Propulsion Laboratory has been delegated the responsibility for pre-formulation study activities, technology development, formulation and

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technology development, formulation and implementation of the mission. The Origins and Fundamental Physics program office is the organizational home for the pre-project at JPL. Within the TPF project, the Interferometer System is accountable for delivering interferometer mission designs validated by technology results.

A *system manager* provides overall leadership of the interferometer effort. An *architecture team* 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 before the downselect. These concerns are retired through a combination of system design and technology development[7]. The *design team* delivers mission designs and an end-to-end simulation that satisfy the system error budget. An *interferometer technology team* and a *formation flying technology team* deliver validated models of testbed and component results which can be extended to the expected flight environments and flight requirements.

Organization	Nature of Collaborations
Ball Aerospace	Design team, structurally connected testbed, formation flying technology
Lockheed Martin	Design team, structurally connected testbed
Northrop Grumman	Design team
Massachusetts Institute of Technology	System modeling, thruster contamination characterization, electromagnetic formation flight control, formation flight demonstration
University of Arizona	Beam splitter, combiner, & phase sensing technology, integrated optics technology, simgle mode waveguide
Tel Aviv University	Single mode fiber

Table 1. TPF Interferometer Contracts

Many others are making valuable contributions to the TPF interferometer effort. The TPF Science Working Group (SWG) consists of leaders in the field from academia, industry, JPL and other NASA centers. The SWG is defining the science requirements for the mission, candidate target lists, and preliminary observation scenarios. ESA is studying its own interferometer planet finder mission. The mission's name is Darwin[8]. The ESA Darwin team is collaborating with the TPFI architecture team about possible free flyer architectures. The Goddard Space Flight Center and members of industry participate in the design team. Both industry and academia are participating in technology development through competitive proposals. Table 1 lists some of the active interferometer contracts.

3. PROJECT SCIENCE

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 that include 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. Interim science requirements[9] are summarized below. The major difference in science requirements between the interferometer and coronagraph concepts is the observing waveband. For the interferometer the required waveband is the mid-IR from 6.5 to 13μm which includes spectral lines for methane (7.7μm), ozone (9.7μm), CO_2 (9.3μm, 10.4μm) and a long wave continuum for water. There is an additional goal of covering a band of 13 to 17μm which includes a more observable line of CO_2 at 15μm. For the coronagraph the required waveband is the visible/near-IR from 0.5 to 0.8μm. There is an additional goal of covering a band of 0.8 to 1.05μm.

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 of at least 150 stars. The system must be capable of completing these surveys within 2 years. To complete a survey of a star its continuously habitable zone must be explored with 95% completeness for terrestrial planets with at least half the surface area of the Earth. Within a more generously defined habitable zone TPF must be able to detect an Earth-sized planet with 95% completeness. The habitable zone is defined as that region around a star within which, instantaneously, liquid water may exist. A planet located in the habitable zone is in principle habitable by water-based life like our own. The continuously habitable zone is the narrower range for which liquid water and hence habitability is possible for geologically significant timescales of a billion years or more. For our sun the habitable zone is 0.7 to 1.5 AU and the contiuously habitable zone is about 0.9 to 1.1 AU. The size of the habitable zones scale in proportion to the square root of the luminosity of the star. The

95% completeness criterion also implies multiple observations of a star system at different times of the year to spot target planets at observable phases of their orbits. Although still the subject of debate the number of times each system must be observed is likely to be at least 3.

The number of stars to be observed is a major engineering driver. Three characteristics of the interferometer most influence the number of stars that can be observed. One is array length. As the array length grows angular resolution gets smaller which implies stars at a greater distance can be observed. The second is aperture size. As aperture size gets larger dimmer objects can be observed or brighter objects can be observed quicker. The third is sky coverage which is chiefly limited by the shade provided by a sunshield. As the sunshield gets larger (or the instrument is articulated relative to the sunshield) the sky coverage improves. The approach is to pursue an SCI architecture that is capable of satisfying the minimum science requirements (> 30 stars) and an FFI concept that is capable of satisfying the full science requirements (>150 stars).

Engineering constraints on array and collecting aperture sizes limit TPF to a survey of relatively nearby stars (<15 parsecs). 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 will 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.

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 close to us, the nearest few have sentimental value and so are prominent on the target list. The ability to observe stars both near and far will be one of the discriminators between the various architectures and configurations.

4. ARCHITECTURE

4.1 Architecture Trades

The TPF Interferometer System architecture team is working with the TPF SWG to select baseline architectures for the minimum and full science missions.

We have considered a large number of entrance pupil configurations[10], for example Bracewell, dual-Bracewell, Degenerate Angel Cross, Angel Cross, OASES, Darwin Laurance, Darwin bow-tie, etc., and at this time have narrowed our trade space by applying the following requirements:

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

The entrance pupil configurations that are still being considered are shown in Figure 1. The key figures of merit for the choice of architectures are the total number of observable stars and the number of observable nearby stars (< 5 parsec). Table 2 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 in Table 2 as the distance between the outermost collectors in a given array measured from the center of the optic. Table 3 lists key parameters in the analysis used to generate the configurations of Table 2. The inner distance at which 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.

Using more than two collecting telescopes allows flexibility in the shaping the null and the suppression of background signal and instrument instabilities via phase chopping.

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

Design Feature	Minimum Science Mission	Full Science Mission				
		(A)	(B)	(C)	(D)	(E)
Platform	Connected Structure	Formation-flying	Formation-flying	Formation-flying	Formation-flying	Formation-flying
Input pupil	Dual Bracewell	Dual Bracewell	Dual Bracewell	Degenerate Angel Cross	Darwin 2-D bow-tie	Darwin 2-D bow-tie
Phase Chopping	Yes	Yes	Yes	Yes	Yes	Yes
Array size	36m	70m	70m	70m	55m	55m
Collecting Area	4 x 3.2m diameter apertures	4 x 3.0m diameter apertures	4 x 4.0m 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	1	2
Instantaneous Sky Coverage (from anti sun)	+/- 45 degrees	+/- 45 degrees	+/- 45 degrees	+/- 45 degrees	+/- 45 degrees	+/- 45 degrees

Table 2: Configuration Summary For Minimum And Full Science Mission.

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

Table 3: Key Parameters Used In Trade Analysis

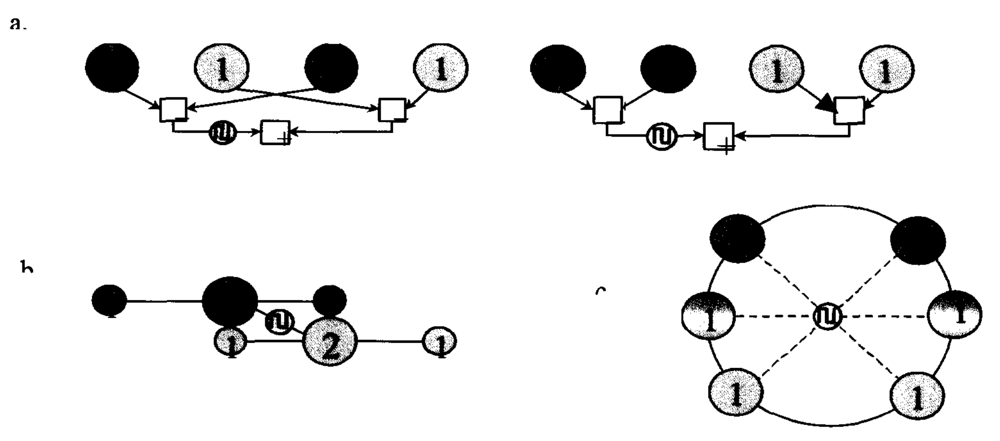


Figure 1: Entrance Pupil Configuration For A) Dual Bracewell, High-Resolutions And Low-Resolution, B) Degenerate Angel Cross, C) Darwin Bow-Tie. Number In Circles Refer To Relative Collective Areas.

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 better the resolution and narrower the null width of the interferometer.

For the SCI resolution is the key limiting parameter, because the array size is restricted by the size of a structure that can be deployed in space. Consequently, we chose a Dual Bracewell entrance pupil - of all the chopping capable entrance pupils, it has the highest angular resolution for a given array length. Table 2 lists consistent parameters enabling 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 sizes in Table 2 were chosen to provide 15m between the edges of ~12m sunshields of the formation-flying spacecraft.

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. Aperture sizes being considered range from 3.0 to 4.0 meters.

4.2 Top Technical Concerns

Flight implementation of any of the interferometer architectures listed in Table 2 represents a significant extension of current capability. The Interferometry Performance Model, a thorough error budget that ties the science requirements to instrument and flight system engineering requirements, is used to quantify the technical concerns of these architectures. Kepner-Trego methods[11] were followed to rank the technical concerns raised for the SCI and FFI architectures. Kepner-Trego methods suggest that concerns be prioritized not only by gap (seriousness) but also by the urgency and the trend of the concern. Each concern was first broken down into technical specifications and quantified using the performance model. Next, the TPF flight specifications were compared to current capability to establish the degree of technical gap. High urgency was assigned if the concern needed to be retired before the 2006 downselect or was a potential showstopper. Concerns that could be deferred to project Phase A/B ending in 2011 were assigned medium or low urgency. Trend for each concern was tied to inheritance. If the concern is expected to be mitigated by development work on another nonflight program or demonstrated by a flight mission, then the trend priority was lowered. Factors important to the assessment of inheritance are: timing of the planned inheritance relative to the TPF mission downselect, the confidence in the future occurrence, and the degree of inheritance (general, evolutionary, or direct).

Table 4 lists those concerns with high or very high priority. These top technical concerns are the basis for deciding what must be addressed before the downselect. The results of this process were reviewed by 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). For example, 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 by the Code R Distributed 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. With the cancellation of the StarLight mission, the technologies associated with precision formation-flying can no longer be directly inherited, and will instead be mitigated through the ground technology program and system engineering design. The

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 accuracy 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	*SE*, J, L, M
	Performance of fine formation control	1 cm range, 20 arcsec 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, 4□ sterarian FOV with no calibration maneuvers	50 cm, 30 deg, 1.3□ 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
	Inters s/c 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, formation flight systems	Self imposed	4 x 3.2m diameter mirrors on separated 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/planet contrast of 10^{-6} over 6.5 -17μm, over 0.1–1 arcsec	Artificial star systems	B

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

Table 3: Top Technical Concerns For Interferometer

likelihood and degree of future inheritance will be monitored for programmatic and technical changes.

5. SYSTEM ENGINEERING

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 that 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 6.

The design team began by developing a draft set of engineering requirements derived from the science requirements and coordinated with the architecture and technology teams. The team then roughed out several important scenarios like launch, deployment, and science observations. Next the team reviewed the very valuable work of others who preceded 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[3]. Some fundamental design goals were specified like fitting each concept onto a single launch vehicle, satisfying requirements with monolithic primary mirrors, and avoiding the use of on orbit assembly. We spent time defining the trade space to be explored. 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.

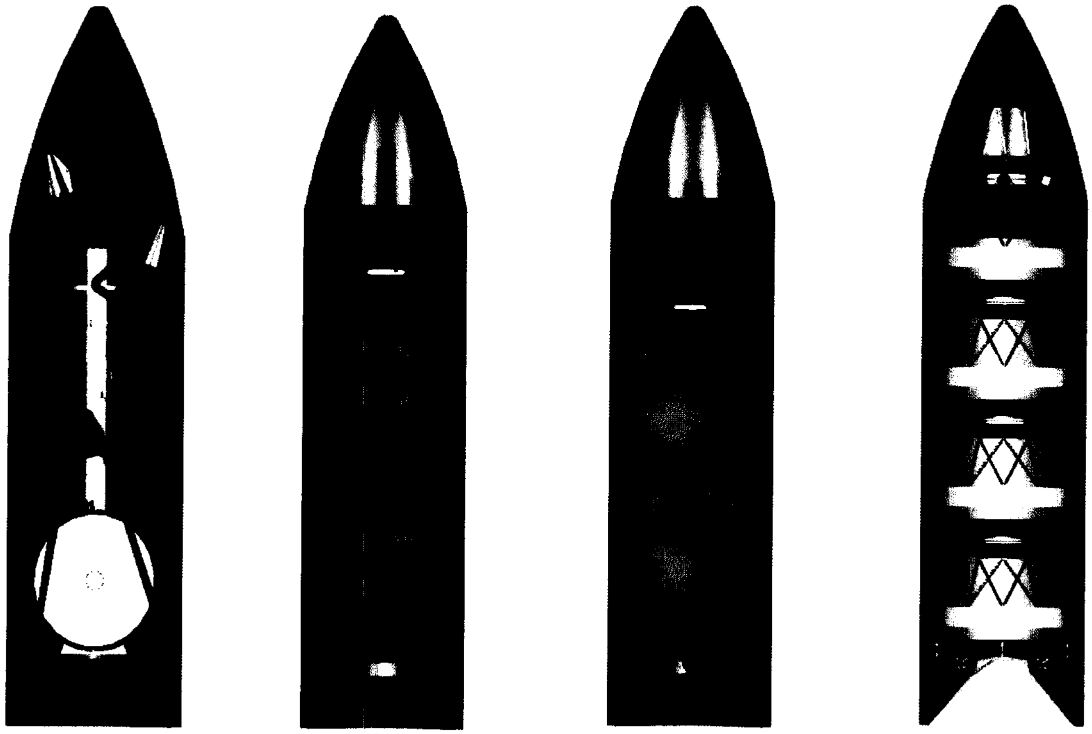
An L2 halo orbit was tentatively selected as a baseline over several options because of its low launch energy, consistent communications geometry, and the opportunity it provides for launch of a spare spacecraft should a previously deployed spacecraft of a constellation fail. Future study of the propulsion stage required to insert the interferometer into a halo orbit may suggest a reconsideration of an Earth trailing orbit. For the launch vehicle trade, 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 trades that follow. Many options have been considered for launch packaging of both the FFI and SCI. Some of the options for each are shown in Figures 2 and 3. In Figure 2 the option on the far right is the current baseline. It has two major advantages. One it allows for the greatest diameter apertures (~4 meters). Two it provides for enclosures of the mirrors until L2 is reached thereby minimizing the potential for contamination. In Figure 3 the option on the far right is the baseline. The chief advantages of this configuration are a low center of mass and simple mechanisms (hinges) for deployment. The two fold designs depends on extendable booms to achieve the 36 m array length. The four fold design has hinges and a rotating mechanism. The six fold inline suffers from a smaller boom cross section which is thought to present less damping of vibrations during science observations than the larger cross section of the oblique configuration.

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).

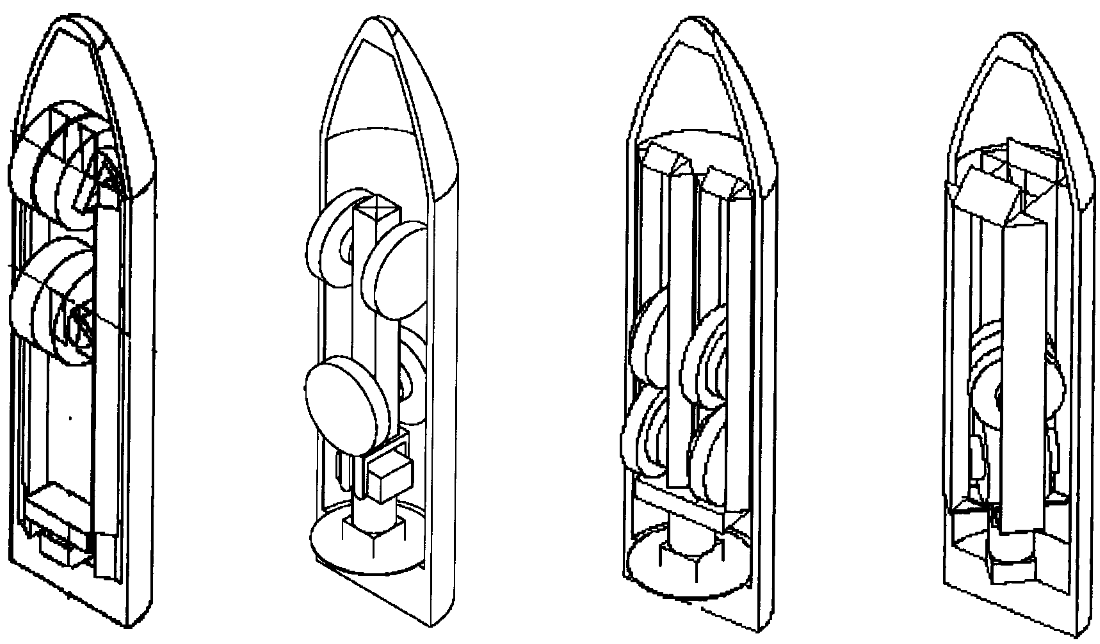
Interferometers by their nature are highly integrated systems that are susceptible to small disturbances. As such, predictions of system performance rely on extensive modeling. Also, the TPF interferometer is too large to test as a complete system before launch. Consequently, software models of the system 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.



Alternating Side-Facing | Face-to-Face Stack | Parallel Side-Facing | Simple Stack

Figure 2. Some Mechanical Configuration Options for the FFI Concept



2-Fold | 4-Fold | 6-Fold Inline | 6-Fold Oblique

Figure 3. Some Mechanical Configuration Options for the SCI Concept

eature	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		
FFI mechanical configuration	4, 5, 6 aperture, various orientations of apertures in launch vehicle fairing	4 aperture (see Figure 4)
SCI mechanical configuration	2-fold, 4-fold, 6-fold inline, 6-fold oblique	6-fold oblique
Power source	Solar arrays, radioisotope	Solar arrays
Coarse formation acquisition sensor	RF, optical, others	RF
Spacecraft intercommunications	Dedicated UHF link, Shared RF link with acquisition sensor, others	Dedicated UHF
Direct to Earth link capability on collector spacecraft	Yes or no	Yes
Gimbal for HGA on combiner spacecraft	None, single axis, two axis	Two axis
Sunshield configuration & deployment	JWST-like, wraparound, free flying	In work
Fine pointing control technology	Colloid, FEEP, reaction wheels, others	In work
Timing of formation or boom deployment	After launch, after orbit insertion	In work
Other subsystem	Many	Planned
Instrument Design		
Telescope optical design	Secondary mirror on/off axis, various focal lengths	In work
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

Table 5. Near Term Trade Study Activities of of the Design Team

6. <u>TECHNOLOGY DEVELOPMENT</u>

Technology development is planned for those top concerns not already addressed by system engineering or planned inheritance. The technology areas described below are grouped by core interferometry, connected structure, and formation-flying. Testbeds produce validated models in addition to providing demonstrations of capability.

Not described below is the Advanced Cyocooler Technology Development Program[12] managed separately at JPL, which is developing engineering model prototypes for JWST, Constellation-X and TPF capable of cooling to 6K. Technology activities for the interferometer concepts are listed in Table

6.1 <u>Core Interferometry</u>

The **<u>Achromatic Nulling Testbed</u>** addresses the optical issues related to achieving deep, broadband, dual-polarization, mid-infrared nulls. The testbed is based on the modified Mach-Zehnder 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

	Technology Activity	Description	Key Intended Result
A	Achromatic Nulling Testbed	Two-beam modified Mach-Zehnder nuller at room temperature then at cryo. Wavelength 6.5 to 12 μm	• Stable 10^{-6} white light null with 50% bandwidth • 10^{-5} off-axis source detection
B	Phasing System Testbed	Four-beam modified Mach-Zehnder, dual-chopped Bracewell, at room temperature in a vacuum, white light	• 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 6.5-17 μm bandwidth
D	Cryogenic Delay Line	Three-stage opto/mechanical cryo mechanism	• Operate prototype closed-loop at 77K • <1 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, and polarization	• Demonstrate 10^{-5} null with a 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.
H	Structurally-Connected 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) 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.
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, off-nominal scenarios
K	Formation Sensor Technology	Hardware development and demonstration of the formation acquisition sensor at S-band	• Demonstrate range and bearing determination with 4□ 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 using multiple mobile vehicles equipped with flight-like avionic hardware and air-bearing on a raised floor	• 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 (MIT)	Three soccer-ball-sized "spacecraft" on International Space Station, ultrasonic range and bearing sensors, gas thrusters	• Demonstrate feasibility of formation-flying in micro-g environment, perform TPF-like array maneuvers
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 tracking across 2 platforms, 30μm/s relative velocity

Table 6. Interferometry System Technology

evaluation, mid-infrared detector and camera selection, alignment algorithm development, and low-level null-control algorithm evaluation. The detection of off-axis sources is demonstrated with a single baseline. The goal is to develop technology that allows 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 predicts performance of a longwave (12-17 μm) nuller. Recently a stable 10^{-6} laser null at 10 μm[13] and a white light null of 10^{-3} have been demonstrated.

The **Phasing System Testbed** is an extension of the Achromatic Nulling Testbed and addresses 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 architecture. The phasing system testbed demonstrates the servo loops and control systems necessary for co-phasing of the four-input nulling interferometer. The emphasis is 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 is developed for the pathlength control and knowledge. Fringe tracking and phasing of four starlight beams is performed to a level of a few nm for white-light nulling. Translational motions of the separate telescopes are simulated while fringe-tracking. Possibilities for demonstration of active and passive amplitude control are being investigated.

Spatial Filters significantly reduce the optical aberrations in wavefronts, making extremely deep nulls possible. The most basic form of spatial filter used in infrared nulling 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 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 develops a low noise, low disturbance, high bandwidth optical delay line capable of sub-nanometer residual pathlength control requirements at cryogenic temperatures.

The objective of the **Adaptive Nuller**[14] is to demonstrate a device that enables significant relaxation of the nulling requirements on the TPF interferometer optical train. The concept actively corrects for wavefront, intensity, and polarization imperfections of the beam train entering the nuller.

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

An **Integrated Optics** task develops 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 dramatically improve its stability.

6.2 Connected Structure

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 30 to 40 meters in length and at temperatures traceable to <40 K improve our ability to predict performance of TPF-class structures. At a minimum, measurements of structures, of ten or more meters in length, are 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 are 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 provides accurate mechanical models for predicting the zero-g behavior of a structurally-connected interferometer at cryogenic temperatures. Component level testing is performed to validate nonlinear models at cryogenic temperatures. System-level structural models are validated where possible using experimental data provided by the Structurally-Connected Interferometer Testbed.

6.3 Formation-Flying

The Formation-Flying Technology testbeds listed in Table 6 are under development to establish the viability of the FFI mission architecture for 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.[15]

The **Formation Algorithms & Simulation Testbed (FAST)** is a distributed real-time testbed using multiple independent computational platforms for end-to-end simulation of the TPF formation-flying system. Fundamental algorithms are developed for the five-spacecraft TPF mission based upon the two-spacecraft algorithms developed for StarLight. The algorithms are demonstrated in the high-fidelity end-to-end simulation environment to the full TPF performance of 5 cm and 5 arcmin accuracy in range and bearing control. Realistic mission scenarios are demonstrated, including formation acquisition, formation calibration, formation maneuvering, re-configuration, and nominal observation. The simulation is further exercised with system fault scenarios to verify the long-term robustness of formation-flying missions. Scenarios include collision avoidance, evaporation of the spacecraft formation, and system-level failures (e.g. thrusters, sensor). The FAST simulation is validated in hardware by the Formation Control Testbed, described below.

The **Formation Sensor Testbed (FST)** provides hardware demonstration of the formation acquisition sensor. Requirements to provide an instantaneous 4π-steradian field-of-view coverage for the estimation of relative range and bearing between multiple spacecraft are verified. Maximum range and bearing uncertainty will be 50 cm and 1 degree over the full coverage. The acquisition sensor is a radio frequency sensor based upon the StarLight Autonomous Formation-Flying (AFF) Sensor.[16] This testbed demonstrates new algorithms for multiple spacecraft operation, tests a passive radar mode for added robustness against collision avoidance, and verifies that time-consuming calibration maneuvers can be eliminated. RF-based performance within a TPF-like structural environment and accommodation constraints are evaluated. FST also provides sensor models used in the FAST system simulation.

The **Formation Control Testbed (FCT)** demonstrates 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. It emulates real spacecraft dynamics using multiple mobile test vehicles equipped with flight-like avionic hardware and inter-spacecraft communication, moving on air-bearings (Figure 4). FCT also provides validation of the FAST. FCT algorithms and prediction of FCT system performance are developed in FAST. FCT system performance is compared to the FAST predictions, thus validating FAST modeling capability to predict TPF performance.

The Synchronized Position Hold Engage Re-orient Experimental Satellites **(SPHERES)** experiment[17], developed and managed by the Space System Laboratory at the Massachusetts Institute of Technology, performs TPF relevant maneuvers with three soccer-ball-sized "spacecraft" in the

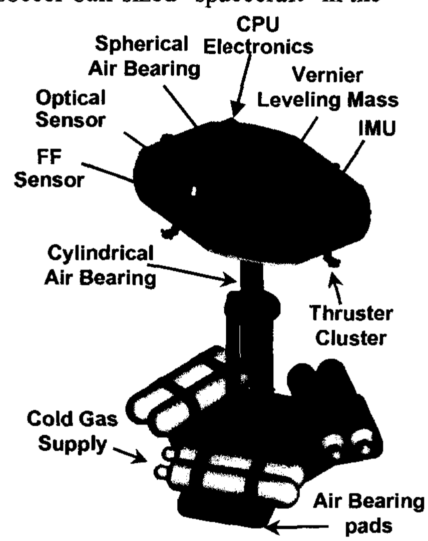


Figure 4. Formation Control Testbed Robot

International Space Station. Each SPHERE is self-contained with ultra-sonic relative sensors, ultrasonic global position sensing, thrusters and inter-spacecraft communication. The experiment demonstrates functional feasibility of formation-flying over a 3m x

3m x 3m test area. It provides lessons-learned for formation-flying.

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

7 SUMMARY

A structurally connected and a formation flying mid-infrared nulling interferometer concept are being designed to support a downselect in 2006 between these architectures and a visible / near-IR coronagraph. The connected-structure is being designed to fully survey at least 30 nearby solar-type stars for the presence of Earth-like (terrestrial) planets and to partially survey 120 more. The formation-flying concept is being designed to fully survey at least 150 stars. A trade analysis determined that a 36m array of four 3.2m diameter apertures on a connected structure meets the minimum science requirements. A trade for the formation-flying architecture is still open, considering nulling arrays based on a dual chopped Bracewell, degenerate Angel Cross, and the Darwin bow-tie configurations. Top technical concerns for each of these interferometer mission concepts were studied and prioritized based on impact, urgency and trend; these top concerns serve as the basis for concurrent system design and technology development activities. Technology efforts include system and component developments in core interferometry, structurally-connected and formation-flying. The authors assert that the plan described in this paper will produce interferometer mission system concepts, validated by technology results for the 2006 mission downselect.

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