

Terrestrial Planet Finder Interferometer: architecture, mission design and technology development

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ABSTRACT

This overview paper is a progress report about the system design and technology development of two interferometer concepts studied for the Terrestrial Planet Finder (TPF) project. The two concepts are a structurally-connected interferometer (SCI) intended to fulfill minimum TPF science goals and a formation-flying interferometer (FFI) intended to fulfill full science goals. Described are major trades, analyses, and technology experiments completed. Near term plans are also described. ¹This paper covers progress since August 2003 and serves as an update to a paper presented at that month's SPIE conference, "Techniques and Instrumentation for Detection of Exoplanets¹."

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

1. INTRODUCTION

The goals of the Terrestrial Planet Finder (TPF) are to discover Earth-like planets around nearby stars and to look for evidence of life. The project science requirements are to survey solar-type stars for terrestrial planets, to characterize these planets and their orbital parameters, and 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^{2,3}. For the mid-IR interferometer concept, two sub-architectures were recommended for further study: a Structurally-Connected Interferometer (SCI, Figure 1) to meet a minimum TPF science and a Formation-Flying Interferometer (FFI Figure 2) version to satisfy the full TPF science requirement. A decision was made this March to proceed with the studies of a coronagraph and FFI but end study of the SCI. The intent now is to launch a coronagraph followed a few years later by a FFI⁴.

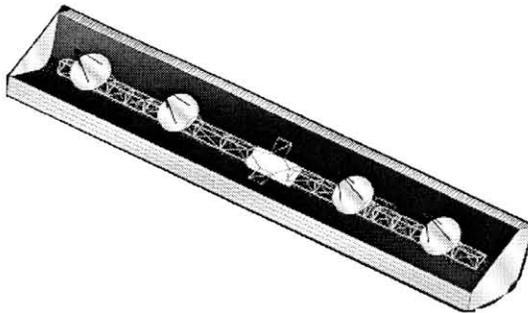


Figure 1. Concept for Structurally Connected Interferometer

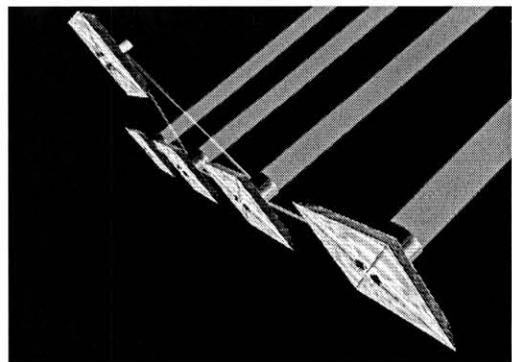


Figure 2. Concept for Formation Flying Interferometer (courtesy Ball Aerospace)

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Nulling interferometry and coronagraphy are different approaches to terrestrial planet detection, but both must cancel the light from a central star to permit detection of a relatively dim planet slightly (0.1 to 1.0 arcsec) off-axis⁵. 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. In nulling interferometry light is combined from multiple telescopes with the phase of each beam pair shifted by π radians, creating a pattern on the sky with 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. Using more than two collecting telescopes allows flexibility in shaping the null and the suppression of background signal and instrument instabilities by phase chopping. 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 mirrors⁶.

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. Within the TPF project, the Interferometer System is accountable for delivering interferometer mission designs validated by technology results.

The European Space Agency's Darwin mission has comparable objectives to TPF⁷. Consequently, ESA and NASA are actively collaborating on terrestrial planet finding concepts that use formation flying as the architecture. There is a near term goal of reaching a joint decision about which particular formation flying architecture should be studied in depth over the next few years.

2. SCIENCE REQUIREMENTS

TPF science requirements are formulated by a science working group (SWG) consisting of members from U.S. academia, government, and industry appointed by NASA and members from Europe appointed by ESA. The requirements have been relatively stable since August 2003. A short review of driving requirements is presented here. A more extensive description is available in Unwin's paper⁸.

The driving requirements on the minimum and full missions are the number of star systems that must be surveyed within a specified time. The current requirements are ≥ 35 systems for a minimum mission and ≥ 165 systems for the full mission. The full mission requirement of 165 is up slightly from the requirement of 150 proposed last August. The number of stars to be surveyed is based on an expectation of the frequency of terrestrial planets of about 1 in 10 systems surveyed and the practical limitations of what can be built within the timeframe of the mission. The time budget for the survey has remained a constant of 2 years following on-orbit commissioning of the observatory. This is not to imply that the first 2 years of the mission will be devoted solely to surveys, rather that 2 years out of the 5 year prime mission lifetime will be budgeted for surveys leaving the other 3 years for characterizations of planets discovered.

A development since August is that the SWG has created a list of potential target stars. The list starts with all stars within 30 parsecs from the HIPPARCOS database, about 2350 stars. Applying science criteria like age, metallicity, spectral type (e.g., F5V through K7V), multiplicity, and others the list of candidate stars has been culled to a shorter list of interferometer candidates of ~ 1000 stars; although, this number is likely to change moderately upon further review. For additional information about the TPF star database see http://sco.stsci.edu/tpf_tldb/.

While "planet finding" is in the name of the project, "planet characterization" is also a major objective. For planet characterization the driving requirements are spectral range and resolution. The required spectral range is still 6.5 to 13 μm with a goal of 6.5 to 17 μm . The requirement for spectral resolution is still 20. The spectral features sought with these wavebands are CO_2 , H_2O , and O_3 which is a proxy for O_2 . There is also a stated desire to observe CH_4 ; although, this is acknowledged as being a greater design challenge.

Very recent developments in the science requirements debate are the anticipation of a requirement for overlap in the lists of stars surveyed by the coronagraph and interferometer. This is so that observations in the visible and infrared spectrums complement each other. There has also been debate about the fields of view of the instruments, the intent being that they be broad enough to view the larger orbits of gas giant planets that are believed to play a major role in the creation of terrestrial planets. For additional details see Mennesson's paper⁹.

3. ARCHITECTURE

The TPF Interferometer System architecture team works with the TPF SWG and ESA to select baseline architectures for the minimum and full science missions and to translate science requirements into engineering requirements.

Much of the architecture team's time in the past months has been spent refining the instrument error budget. This work is described in detail in a paper by Lay and Dubovitsky¹⁰. The goal is a signal to noise ratio of greater than five. The principal findings of the error budget work are that systematic errors dominate. Control of the signal amplitude must be better than 0.1% rms. Control of phase must be better than 1.5 nm rms. Null depth must be better than 10^{-6} . Cross-terms of amplitude and phase are major contributors to the budget.

Another thrust of architecture team work has been refinement and application of star count analyses. After the SWG finishes culling the star database using science criteria, the architecture team applies engineering criteria like distance to the star (integration time), ecliptic latitude (<45 degrees for FFI, <60 degrees for SCI), and others to produce an estimate of the number of systems that can be surveyed within the 2 years allocated. The estimate today for the FFI concept is ~160 systems and for the SCI concept ~35 systems. These estimates assume four 4-meter apertures for the FFI and four 3.2-meter apertures for the SCI. The FFI array length is allowed to vary between 60 m and 100 m. The SCI array length is fixed at 36 m. Both configurations are assumed to be linear, dual-chopped Bracewell arrays.

Working with ESA the NASA architecture team has extended its trade study of multiple architectures¹¹. The results of some preliminary analysis are shown in figure 3. For this analysis the collecting area of the arrays was normalized. Some words of caution in interpreting these results. The star count for the SCI is higher than the "official" star count because a planet radius of one Earth rather than the required half Earth was assumed. Also, one should not assume that the array with the maximum number of stars will be the option chosen. Many other aspects of these designs have not yet been compared and will figure prominently in the final outcome. Examples of these other factors are collector spacecraft design commonality and beam combination complexity. ESA and NASA are working jointly to identify a complete list of significant discriminators and to conduct the analyses these discriminators dictate.

	Aperture Diameter (m)	Minimum Length (m)	Modulation Efficiency	Ports/detector	# of Stars
DCB FFI	3.2	60	0.57	1	224
DCB SCI	3.2	36	0.45	1	84
Bow-Tie	2.6	60	0.21	1	124
Triangle	3.7	20	0.47	0.5	181
X-Array	3.2	40	0.44	1	206
<i>Assumptions</i>					
Throughput	10%		Spectral band	7-17 μ m	
Planet radius	1 Earth		Sky coverage	+/-45 deg	
Planet Temp	260K		Available time	1 year	
			Star list	TPF-I ver. 2	

Figure 3. Comparison of Performance of Several Architectures with Collecting Area Normalized

The X-array is a new architecture (Figure 4). It offers the advantages of decoupling control of the resolution baseline from the control of the nulling baseline and having collector spacecraft designs that are nearly identical. A disadvantage

of this concept is that the direction of the entry ports for the combiner must be adjustable in flight. The transmission pattern for this concept is shown in Figure 5.

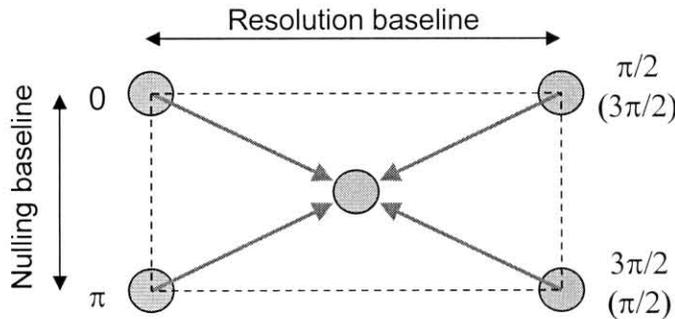


Figure 4. X-Array Architecture Concept

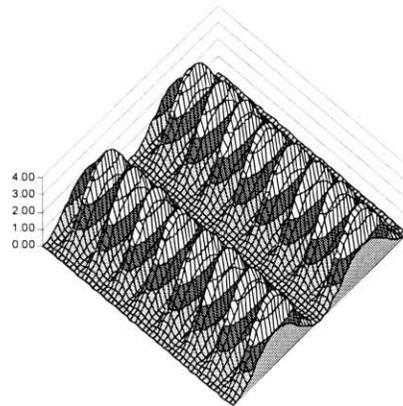


Figure 5. Transmission Pattern of X-Array.

4. MISSION AND FLIGHT SYSTEM DESIGN

The interferometer design team benefits from the addition of several new team members. Goddard Space Flight Center has the role of delivering the telescope design for the project. The Lockheed Martin (Sunnyvale) and Northrop Grumman (Redondo Beach) companies have joined Ball Aerospace as system engineering consultants to the team. With them come their experiences in the development of key precursor missions like the Hubble Space Telescope, Spitzer Space Telescope, Space Interferometry Mission, Kepler Mission, and the James Webb Space Telescope.

Design team activities since August have focused on completing end-to-end conceptual designs to seed detailed design analyses to assess whether the initial error budget can be achieved. Conceptual designs are nearing completion and the team is poised to begin these analyses in earnest over this summer and fall. Papers by Levine¹² and Ware¹³ provide details about the modeling plans.

A key assumption of the error budget was found to be reasonable when the optical throughput of the SCI design was analyzed. The result was a prediction of about 20% which was comfortably above the 10% assumed in the error budget. This prediction while for SCI will be useful for the FFI design as the number of optical elements, especially transmissive optics, is expected to be comparable.

Finite element analysis was conducted of the SCI in the launch configuration. This analysis showed that additional structure had to be added to stiffen the stack to meet launch vehicle minimum dynamic frequency requirements. Additional analysis of the SCI in the deployed configuration is planned before closeout of the SCI study July 1.

A key trade study for the SCI design was consideration of the expansion of its field of regard. The design in August provided a view of +/-45 degrees above and below the ecliptic plane. This view was limited by the size of the multi-layer sunshield that passively cools the optics to about 40K. Figure 6 shows that a +/-60 degree field of regard represents a practical goal for observing additional stars. The questions became how much larger and heavier did the sunshield (figure 7) have to grow to satisfy this goal. The answers are that the shield widths must grow about 2.5 m on each side and the lengths about 5 m with a corresponding mass increase of roughly ???kg.

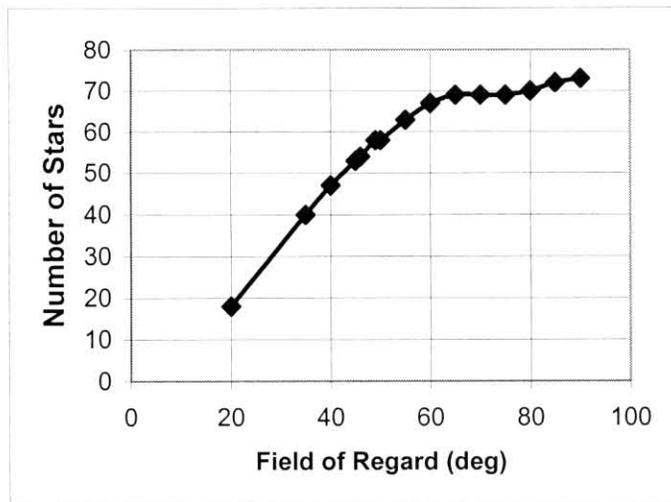


Figure 6. Potential Performance of SCI Arrays vs. FOR

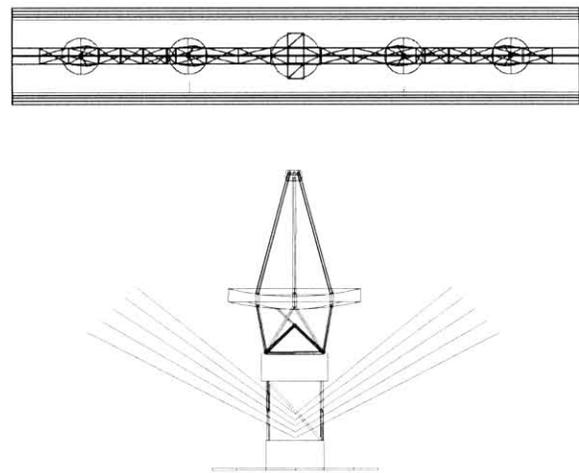


Figure 7. Concept for SCI Sunshield

Much time has been spent developing concepts for the SCI telescope and instrument. Much of this work is applicable to the FFI concept so the recent decision to end study of the SCI has not diminished the value of this instrument work. Concepts have been identified to control pointing, phase, and intensity. Figure 8 shows the concept for phase control and is representative of the maturity of the other concepts. Work now is focused on the mechanical details of the instrument bench (nuller, science detectors, etc.) to support structural and thermal analyses.

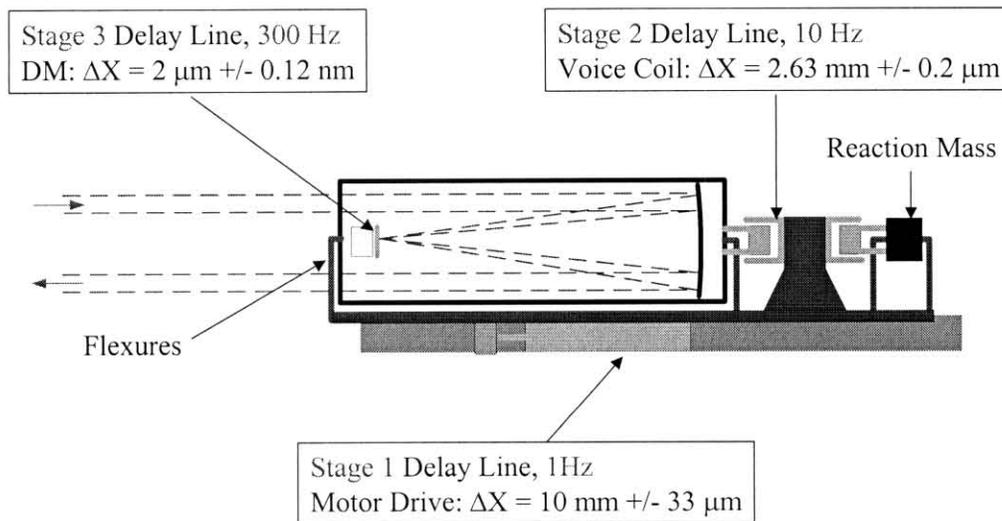


Figure 8. Concept for Phase Control for the TPF-I Instrument

A number of important trades and analyses were completed about the FFI concept. Many of these analyses were conducted by team members from Ball Aerospace. Details about this work can be found in Miller's paper¹⁴. Some highlights are discussed here.

A study was conducted to assess how closely adjacent spacecraft can be positioned to each other. Factors considered were radiative thermal coupling, collision avoidance, and plume impingement. The conclusion was collision avoidance was the driving requirement. The recommendation is that the minimum spacing between sunshields (i.e., wingtip-to-wingtip) separation be greater than about 2.5 m to provide sufficient time to react to attitude faults. Associated with this

trade was a first cut at a fault tree for faults specific to formation flying. A next step is to identify potential mitigations for each of these faults.

An analysis was also conducted that revealed a limitation on the maximum array length. The limitation turns out to be stray light from the intermediate (warmer) sunshield layers of adjacent spacecraft. This light is an error source (noise) of great concern as it is orders of magnitude larger than the target planets' light. Stray light can be blocked by baffles, but the dimensions of these baffles are constrained by formation geometry, sunshield dimensions and packaging for launch. With the current concept it is estimated that the maximum array length is constrained to about 100 m which, conveniently, is the assumption that has been used in the star count analyses to date.

Finite element models of the spacecraft in the launch configuration and deployed were completed. A second cut thermal model for the deployed configuration was completed. Application of these models is now underway. Initial results from the thermal model suggest a challenge meeting the requirement for optics to be <40K. This was anticipated and options to solve this problem will be explored in the coming months.

Major changes are in store for the FFI concept in the coming months. Mass margin estimates dictate that launching the formation on multiple launch vehicles be considered. This means a new packaging concept needs to be created and the challenge of getting the formation together at the final orbit must be studied. In addition, the team plans to begin study of the X-array architecture with the intent of bringing the maturity of understanding of that option up to par with the understanding of the linear array in time for the architecture decision to be discussed with ESA this fall.

5. TECHNOLOGY DEVELOPMENT

Technology development is planned for those top concerns not already addressed by system engineering or planned inheritance. Testbeds will produce validated models in addition to providing demonstrations of capability. Not described below is the Advanced Cryocooler Technology Development Program¹⁵, managed separately at JPL, which is developing engineering model prototypes for TPF capable of cooling to 6K. Additional details can be found in Lindensmith's paper¹⁶.

There have been several programmatic changes to the interferometer technology effort since August. The recent decision to cease the study of the SCI option resulted in the termination of the Structurally Connected Interferometer testbed which was to investigate structural deformations of scale model trusses at cryogenic temperatures. Added are several efforts led by investigators from universities. These efforts are to study potential technology candidates for TPF that were not under study by the NASA team. As these efforts have just started there are no major results available yet, but some major milestones are expected within the coming year.

The principal investigator for the **Electromagnetic Formation Flight** testbed is Dr. David Miller of the Massachusetts Institute of Technology (MIT). The goal of this testbed is to demonstrate that the relative ranges and bearings of multiple spacecraft can be controlled by varying an electromagnetic field produced using orthogonal loops of high temperature, superconducting wire. The approach uses two robots floated on air bearings on a test floor. Each robot has two vertically mounted, orthogonal coils.

Dr. David Miller is also the principal investigator for the **Model Verification** study. The goal of this study is to quantify modeling uncertainty factors. Modeling uncertainty factors will be critical to debates about development and flight readiness since it will be impossible to verify performance of the observatory system by an end-to-end test because of its large size, cryogenic operational temperatures and the effects of gravity.

The principal investigator for the **Propulsion Contamination** test program is Dr. Manuel Martinez-Sanchez also of MIT. The goal of this effort is to measure the potential for contamination of several candidate thruster technologies. This effort includes development of plume models that include IR radiation signatures, direct measurement of IR radiation between 8 to 16 μm of thruster plumes, and direct measurement of depositions on quartz crystal microbalances at <40K. The thruster technologies currently planned for study are Hall thrusters using xenon, helium, neon, and perhaps Argon and RF ion thrusters.

The principal investigator for the **Common Path Phase Sensing** testbed is Dr. Phillip Hinz of the University of Arizona. 10-6 nuller The goal of this effort is to demonstrate ???

Dr. Hinz is also the principal investigator for the **Mid-IR Beamsplitter**. This effort will investigate three different approaches to the beamsplitting: single-pass (sandwich), windmill, perforated.

Figure 9 summarizes testbeds for core interferometry and cryogenic structures that existed in August and that are still planned. “Key Intended Results” in italics have changed since August. In most cases the changes were descope because of budget adjustments. Highlights of progress for some of these testbeds follow. Testbeds not mentioned are still in work but have spent the past months planning and building for upcoming milestones.

Technology Activity	Purpose	Key Intended Results
Achromatic Nulling Testbed	Physics of achieving deep, broadband, dual-polarization, mid-infrared nulls. Operation at cryo temperatures. Show TPF spectral band can be covered by at most two nullers	<ul style="list-style-type: none"> • 10-4 null, 20% BW @ cryo • 10-6 null, 25% BW @ room temperature
Planet Detection Testbed	Address issues of system complexity and techniques for system stabilization and noise suppression necessary to detect a planet. Demonstrate the servo loops and control systems necessary for co-phasing of a four-input nulling interferometer. Demonstration of instrument stability and noise suppression techniques (e.g., phase chopping needed to detect a planet).	<ul style="list-style-type: none"> • planet detection and null depth of $\leq 10^{-5}$ of laser light can be maintained for \geq one minute in the presence of existing laboratory disturbances • planet extraction (flight-like chopping) and null depth of $\leq 10^{-6}$ of laser light can be maintained for \geq one minute in the presence of existing laboratory disturbances
Mid-Infrared Spatial Filter Technology	Reduce the optical aberrations in wavefronts, making extremely deep nulls possible. Investigate performance of single-mode fiber-optics made from halogenide polycrystals or chalcogenide glasses, waveguide structures micro-machined in silicon, or the use of photonic crystal fibers.	<ul style="list-style-type: none"> • 50% throughput over 6.5-17 μm bandwidth
Cryogenic Delay Line	Provide pathlength compensation that makes measurement of interference fringes possible. Develop a low noise, low disturbance, high bandwidth optical delay line capable of sub-nanometer residual pathlength control requirements at cryogenic temperatures ¹⁷ .	<ul style="list-style-type: none"> • Operate prototype closed-loop at 77K • <1 nm rms
Integrated Optics	Reduces weight, size and complexity of the nuller and could dramatically improve stability.	<ul style="list-style-type: none"> • Monolithic two-beam nuller, 5×10^{-5} null depth with 20% bandwidth at 10 μm.
Adaptive Nuller	Actively correct for wavefront, intensity, and polarization imperfections of the beam train entering the nuller thereby permitting relaxation of tolerances on other optical elements ¹⁸ .	<ul style="list-style-type: none"> • Demonstrate wavefront amplitude control to precision of $\leq 0.2\%$ and phase ≤ 5 nm over a spectral bandwidth of >3 μm in the mid IR for two polarizations
IR Optical Materials and Coatings	Procure and test components and coatings for beamsplitters, compensators, windows lenses, mirrors, diffraction elements, polarizers, etc.	<ul style="list-style-type: none"> • Components of broadband performance within 6.5 -17 μm range at cryo temperatures.
Cryogenic Structures Modeling and Technology	Testing of mechanical properties (especially damping) of materials and components at cryogenic temperatures.	<ul style="list-style-type: none"> • Models that accurately predict component & system-level performance of FFI flight structures

Figure 9. Technology Testbeds for Interferometry and Cryo-Structures

A 10^{-4} null at 30% bandwidth centered on 10 μm was achieved using the **Achromatic Nulling Testbed**. Discovery of an existing 10000K temperature source for this testbed will enable testing to an order of magnitude deeper at room temperature. Additional details about this testbed are available in papers by Vasisht¹⁹ and Wallace²⁰.

The **Cryogenic Structures Modeling and Technology** task tested the variation of damping for more than 10 materials over a temperature range of room ambient to 40K. This task was originally focused on verifying components and materials for SCI. It will be redirected to study components and materials under consideration for FFI designs. It is likely that some of the materials already tested for SCI will be used for FFI.

The Formation-Flying Technology testbeds summarized in Figure 9 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.²¹

Technology Activity	Purpose	Key Intended Result
Formation Algorithms and Simulation Testbed	Demonstrate algorithms for the control of a multi-spacecraft formation in a distributed real-time environment.	<ul style="list-style-type: none"> • Demonstrate full TPF performance of 2 cm and 5 arcmin in range and bearing control, off-nominal scenarios
Formation Sensor Technology	Demonstrate sensor technology for relative bearing and range measurements of formation flying spacecraft including a radar mode for formation robustness to sensor faults in flight.	<ul style="list-style-type: none"> • Demonstrate range and bearing determination with 4π steradian field-of-view coverage with maximum uncertainty of 50 cm and 1 degree in range and bearing
Formation Control Testbed	Provide a hardware platform for verification of software unique to formation flight. Provide platforms for testing relative position sensors should future funding permit.	<ul style="list-style-type: none"> • Demonstrate end-to-end autonomous formation-flying in a 1-g environment with performance of 5 cm maximum uncertainty in range and 60 arcmin in bearing control
SPHERES Flight Experiments (MIT)	Flight demonstration of formation flight ²²	<ul style="list-style-type: none"> • Demonstrate feasibility of formation-flying in micro-g environment, perform TPF-like array maneuvers
Formation Interferometer Testbed	Demonstrate interferometry on moving platforms.	<ul style="list-style-type: none"> • Demonstrate optical interferometer fringe acquisition and fringe tracking across two platforms, 30 $\mu\text{m/s}$ relative velocity

Figure 10. Technology Testbeds for Formation Flight

Formation flight control algorithms for a two spacecraft formation were demonstrated successfully on the distributed real-time system of the **Formation Algorithms & Simulation Testbed (FAST)**. Next up is software tailored for control of the Formation Control Testbed robots. An initial version of this software has already been delivered. Another delivery with extended capabilities is expected in August.

The Ultra Binary Offset Carrier signal to be used to demonstrate coarse estimation of relative bearing and range was successfully generated and tracked on prototype units of the **Formation Sensor Testbed (FST)**. Coming up are tests to demonstrate use of this signal on two spacecraft.

The **Formation Control Testbed (FCT)** will use three robots like the one shown in Figure 11. Integration of the first of these robots is underway as evidenced by Figure 12. The first robot is to be delivered this September. It will emulate real spacecraft dynamics using multiple mobile test vehicles moving on air-bearings and equipped with flight-like avionic hardware and inter-spacecraft communication.

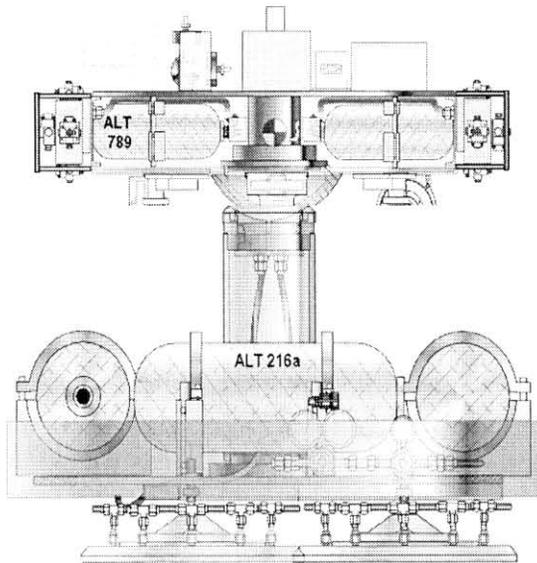


Figure 11. Design of Formation Control Robot
(courtesy Guidance Dynamics Corporation)



Figure 12. Assembly of Formation Control Robot #1.

6.0 SUMMARY

Progress has been made in the design of and technology development for the TPF interferometer. Some things have been learned and some new questions spawned. With the help of new partners, several major trades and conceptual designs of assemblies were completed. Some first-cut analyses were also completed. Holes in the conceptual design are almost all filled so that other types of detailed analyses can begin to assess whether the initial error budget can be achieved. It won't of course so plans exist to continue designing and testing technology.

ACKNOWLEDGMENTS

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