Technology for a Mid-IR Flagship Mission to Characterize Earth-like Exoplanets

Mid-Infrared Nulling and Formation Flying Technology Whitepaper

Abstract: The exploration of Earth-like exoplanets will be enabled at mid-infrared wavelengths through technology and engineering advances in nulling interferometry and precision formation flying. Nulling interferometry provides the dynamic range needed for the detection of biomarkers. Formation flying provides the angular resolution required in the mid-infrared to separately distinguish the spectra of planets in multi-planet systems. The flight performance requirements for nulling have been met and must now be validated in a flight-like environment. Formation-flying algorithms have been demonstrated in the lab and must now be validated in space. Our proposed technology program is described.

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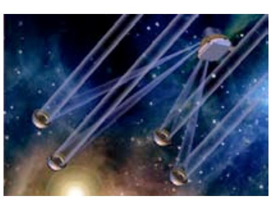

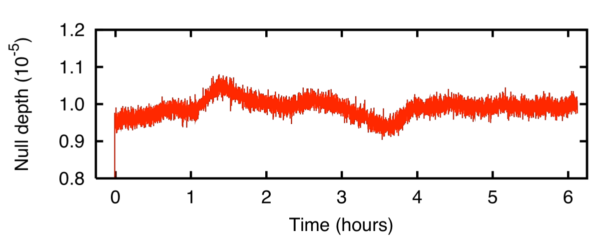

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1. Introduction

A flagship mid-IR mission would enable the search for biosignatures in the spectra of nearby Earth-like planets with the highest angular resolution of any of the exoplanet mission concepts currently being proposed.

An interferometer is a compelling choice for the overall design of a flagship mission. At mid-infrared wavelengths the angular resolution needed to resolve an Earth-Sun analog at a distance of 10 pc is ~50 mas, so that a conventional single-telescope design would need a primary mirror with a diameter larger than 40 m. By using separated apertures, baselines of hundreds of meters are possible. Nulling interferometry is used to suppress the on-axis light from the parent star, whose photon noise would otherwise overwhelm the light from the planet (Bracewell 1978). Off-axis light is modulated by the spatial response of the interferometer: as the array is rotated, a planet produces a characteristic signal, which can be deconvolved from the resultant time series (Bracewell 1978; Léger et al. 1996; Angel & Woolf 1997). Images of the planetary system can be formed using an extension of techniques developed for radio interferometry (Lay 2005).

The Emma X-Array formation-flying design is the culmination of more than a decade of study by NASA and ESA (cf., Cockell et al. 2009). This architecture uses four identical collector spacecraft and provides almost full sky coverage over the course of a year. It simplifies the optics, eliminates the deployable structures used in previous designs, and greatly reduces the overall launch mass. Light from the target star is reflected from the four collector mirrors (2-m diameter) and focused onto the input apertures of the combiner spacecraft approximately 1 km away. To observe a target system, the collector array is rotated slowly about the line-of-sight, using a combination of centimeter-precision formation flying and careful attitude control to maintain the pointing of the beams. Optical delay lines are controlled through fringe tracking on the combiner spacecraft to provide the nanometer-level stabilization of the null.

A key advantage of the X-Array configuration is its very high angular resolution. Over a period of two years, a mission with 2-m diameter collectors would be capable of detecting more than 130 Earth-sized planets and measuring the spectra of 70, assuming $\eta_\oplus = 1$ (Lay et al. 2007). Target stars would include F, G, and K spectral type, but also a large number of M stars accessible to the interferometer. Following a candidate planet detection and follow-up confirmation, a longer period of observing time is dedicated to spectroscopic characterization, using the same observing procedure as for the initial detection. Details of a design study for the array are given by Martin et al. (2008a). A more detailed description of mid-infrared biomarkers is given by Des Marais et al. (2002).

This technology whitepaper is a companion paper to the TPF-I response to the Astro2010 Request for Information (submitted separately). The technology described in these pages has grown from the legacy of the Terrestrial Planet Finder (TPF), which with its counterpart in Europe, the Darwin mission, have been studied and reviewed since the mid-1990s (cf., Beichman et al. 1999; Fridlund et al. 2000). Technology development for TPF was endorsed by the McKee-Taylor report at the beginning of the 2000–2010 decade, with the goal of enabling a mission sometime after 2010.

Here we report on the success of NASA's investment in TPF-I and detail a strategy for mission development. Further sustained effort is needed in the coming years to address several of the risks associated with a flagship mission. Table 1 provides a summary of the proposed technology program, which focuses on the cryogenic validation of nulling technology and in-space testing of formation flying. Funding at the level of $300M in the 2010–2020 decade would bring cryogenic nulling technology to TRL 6, and enable an international collaboration in space-based precision formation flying, bringing the technology to TRL 9.

Table 1. Technology Development Schedule

Activity	Timeline	Cryogenic Nulling Interferometry
Component validation	Years 1–2	Cryogenic testing of components, including single-mode mir-IR fibers, fast steering mirrors, actuators, and deformable mirrors
Subsystem validation	Years 3–5	Cryogenic testing of subsystems, including delay lines, achromatic phase shifters, and an adaptive nuller
System testing	Years 6–9	Cryogenic system testing of 4-beam nulling interferometry in a flight-like environment with flight-like hardware: planet signal extraction using array rotation and chopping; instability noise suppression; biomarker characterization
Activity	**Timeline**	**Formation Flying**
Space-based Formation Flying Demonstrations	Years 1–9	Collaboration in space-based experiments in guidance, navigation & control, including thruster and sensor technology, and interferometric beam combining

Cryogenic Nulling Interferometry

The mission relies on the ability to suppress starlight below the level of other sources of photon noise. Laboratory tests of interferometric nulling have now demonstrated starlight suppression at the level required for flight. The tests were conducted in an ambient lab environment (at room temperature), rather than a cryogenic vacuum, and used a 34% bandwidth centered at a wavelength of 10 microns. These tests demonstrated that the components and subsystems for starlight suppression are at TRL 4 (TRL 5 would require cryogenic testing). System-level tests, using four instead of two combined beams, have not yet been completed but are underway.

With regard to starlight suppression, almost all the work that can be done at room temperature has now been completed. The greatest gain would be had with a transition to cryogenic testing of components, subsystems, and systems, and the development of mature brassboard designs. This should be the focus of efforts in the early 2010–2020 decade.

Precision Formation Flying

The major mission risk is the reliance on a simultaneous and coordinated use of five separate spacecraft flying in formation; four telescopes each on separate spacecraft and an additional spacecraft used as a beam combiner. Guidance, navigation, and control demonstrations in the lab have shown that such control is feasible, with performance traceable to flight. However actual hardware tests in space have not yet been performed to address mission requirements.

In-space testing is necessary in the 2010–2020 decade to raise the TRL level of formation flying. This work should be done through an international collaboration and leverage both US and European expertise in separated-spacecraft rendezvous and docking.

Cryogenic Technology and Engineering

A flagship mid-infrared mission would be a cryogenically cooled observatory, and so shares many aspects of technology development with JWST, including the use of cryo-coolers, passive cooling, thermal shields, and cryogenic actuators. It also shares with Herschel the need for light-weight Silicon Carbide mirror technology. Although challenging, these technologies are expected to be mature by the time that TPF-I or Darwin launches. The major challenges are primarily those of the cryogenic engineering of a complex instrument.

2. Starlight Suppression

Nulling Interferometry and the Detection of Earth-like Planets

An Earth-like planet around a Sun-like star would appear about 10^7 times fainter than the star. To reach an Earth-like planet, a series of steps must be taken:

1. The star's apparent intensity must be reduced relative to the planet by a factor of 10^5 through interferometric nulling.
2. The interferometer array must be rotated around the line of sight to the star to search the whole region around the star for a characteristic planet signature. During this rotation, stable nulls need to be maintained.
3. The planet signal is modulated against the bright background of zodiacal and exozodiacal light. This is done using phase chopping. The combination of rotation, phase chopping, and averaging over time reduces the noise level by a factor of 100 to 10^{-7} of the stellar intensity.
4. The technique of spectral fitting uses correlations between null fluctuations across the spectral band to reduce the instability noise. This yields a further factor of 10 in reduction of the noise level.

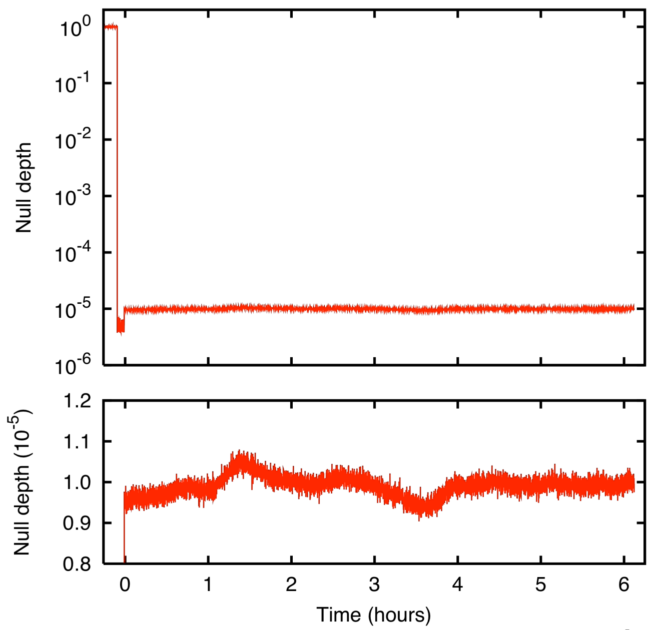

Figure 1. Mid-infrared nulling at the flight-requirement of 10^{-5}, using a central wavelength of 10 microns, no polarizing filters, and a bandwidth of 34%. (Peters et al. 2009)

Thus, the combination of these four techniques yields the necessary performance.

Broadband Starlight Suppression

Results obtained in the lab have met the Pre-Phase A requirements for a flagship mission. Laboratory work with the Adaptive Nuller has demonstrated mid-infrared nulls of 1.0×10^{-5}

with a bandwidth of 34% and a mean wavelength of 10 μm; this demonstrates that at the subsystem-level the nulling performance for a flagship mission is near TRL 4 (cryogenic testing would be needed for TRL 5). These results also show that the achromatic phase shifters, the Adaptive Nuller, and the mid-infrared single-mode fibers that are contributing to these results are now mature technology. These results are shown in Figure 1. Others results of note are included in Figure 2, which illustrates the experiments undertaken since 1999.

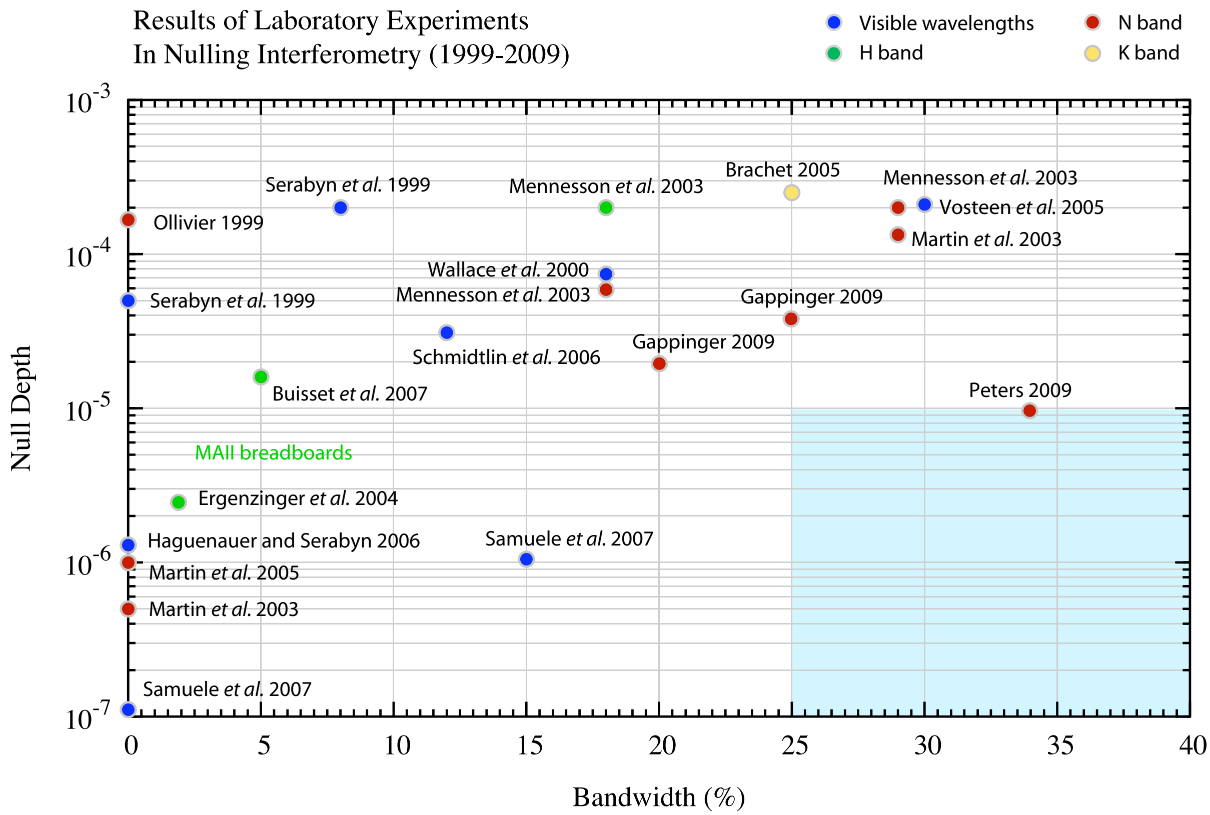

Figure 2. Chart of null depths achieved since 1999. The blue shaded area highlights the nulling performance needed to be demonstrated in the lab in preparation for a flagship mission. (P. R. Lawson, JPL)

These results were achieved by Adaptive Nulling and was the goal of the project's Milestone #1 and Milestone #3 (See Section 6 for links to the full Milestone Reports). No further room-temperature demonstrations are necessary in broadband nulling. The greatest advance would now be to repeat this demonstration in a flight-like environment.

Planet Detection with Chopping and Averaging

Further noise suppression is required in addition to starlight suppression. Nulling can reduce the glare of starlight to a level fainter than the warm glow of local zodical dust (surrounding our Sun) and exo-zodiacal dust (around the target star), but the planet itself may still be 100 times fainter.

The first step is to suppress the response to any thermal emission that is symmetrically distributed around the star. In principle this will remove the detected glow of local and exozodiacal dust. By rotating the array and averaging the response, the planet signal can be further enhanced. The beam combiner for TPF/Darwin therefore combines two pairs of beams to null the starlight, and the beam combining system modulates the response on the sky (keeping the star nulled) by chopping back and forth between these nulled pairs. This milestone (Milestone #4) has been detailed by Martin et al. (2008b), and is listed with other milestones in Section 6.

Laboratory work is well advanced to demonstrate the detection of planet light with the Planet Detection Testbed. Simulated planets two million times fainter than a star have been detected in early trials. Although these tests represent the full complexity of beam combination, this research is being conducted at room-temperature in air, and the noise properties of the testbed are therefore unlike those that would be met in flight. We expect this milestone will be completed by the Planet Detection Testbed in 2009.

Systematic Noise Suppression

An additional step is required to suppress the noise down below the typical brightness of an Earth-like planet. After nulling and chopping, the dominant source of noise is due to residual instabilities in the null depth, which generates a 1/f-noise of similar intensity to the planet signal. This noise can be suppressed by appropriate choice of interferometer baselines and by filtering the measured data from a complete rotation of the array. We expect this milestone (Milestone #5) will be completed in 2009–2010.

Additional technology progress beyond this milestone would depend on cryogenic testing of components and systems.

Cryogenic System Testing with a Flight-like Interferometer

The final demonstration of the feasibility of nulling for a flagship mission would be to integrate all the necessary components in a vacuum cryogenic testbed. This would demonstrate the full system complexity and include flight-like servo systems and brass-boards. The path towards that goal will entail cryogenic testing of components and subsystem, as indicated in Table 1.

Mid-IR Spatial Filters

Spatial filters can be used to reduce complex optical aberrations in the incoming wavefronts to simple intensity and phase differences (which are more readily corrected), thus making extremely deep nulls possible. Examples of single-mode mid-infrared fibers have already been successfully demonstrated with chalcogenide glass and silver halide materials.

20-cm long chalcogenide fibers have demonstrated 30-dB rejection (a factor of 1000) of higher order modes with an efficiency of 40%, accounting for both throughput and Fresnel losses (Ksendzov et al. 2007). The transmission losses were measured to be 8 $dB \cdot m^{-1}$, and the fibers are usable up to a wavelength of about 11 μm.

10–20 cm long silver halide fibers have demonstrated 42-dB rejection (a factor of 16,000) of higher order modes with transmission losses of 12 $dB\ m^{-1}$ (Ksendzov et al. 2008). Silver halide fibers should in principle be usable up to a wavelength of about 18 μm, although the lab tests were conducted only at 10 μm. This was the first time silver halide fibers were demonstrated to have single-mode behavior.

It would be greatly advantageous to improve the throughput of these devices, to test them throughout the full wavelength range they are intended for, and to test them cryogenically. Spatial filter technology would then be at TRL 5. It would, furthermore, be advantageous to implement mid-infrared spatial filters and beam combiners using integrated optics, so as to reduce the risk associated with the complexity of the science instruments.

Cryogenic Adaptive Nulling

The Adaptive Nuller was designed to correct phase and intensity variations as a function of wavelength in a nulling interferometer. This has not only allowed nulling at 1×10^{-5}, but also substantially reduced the requirements on the nulling interferometer's optical components. The results of this research have been published by Peters et al. (2008), who demonstrated phase compensation to better than 5 nm RMS across the 8–12 μm band and intensity compensation to better than 0.2% RMS.

Adaptive nulling is straightforward to generalize over a full science band, and it should be demonstrated within a cryogenic vacuum, bringing the technology to TRL 5. This would necessitate the successful validation of cryogenic spatial filters (above) and the testing of a cryogenic deformable mirror.

Integrated Modeling

High-fidelity modeling is needed to predict the behavior of the observatory when subjected to realistic dynamic disturbances (e.g., from reaction wheels). Such a model would need to be validated with experimental results from a cryogenic system testbed and would provide confidence for the observatory error budgets. These results could then be used to predict the depth and stability of the starlight null over the entire waveband to the limits required in flight to detect Earth-like planets, characterize their properties, and assess their habitability.

3. Cryogenic Technology and Engineering

Almost all the required cryogenic engineering for a mid-IR flagship mission can be adapted from prior work. The following paragraphs describe the progress to date in each of the relevant areas.

Cryogenic delay lines

The Dutch company TNO Science and Industry led a consortium that developed a compact cryogenic Optical Delay Line (ODL) for use in future space interferometry missions such as ESA's Darwin and NASA's TPF-I. The prototype delay line is representative of a flight mechanism. The ODL consists of a two-mirror cat's eye with a magnetic bearing linear guiding system. TNO and its partners have demonstrated that accurate optical path-length control is possible with the use of magnetic bearings and a single-stage actuation concept. Active magnetic bearings are contactless, have no friction or hysteresis, are wear free, and have low power dissipation. The design of the Darwin broadband ODL meets the ESA requirements, which are an OPD stroke of 20 mm, stability of 0.9 nm RMS (with a disturbance spectrum of 3000 nm RMS, < 20 mW power dissipation (2 mW with flight cabling), output beam tilt < 0.24 microradians, output lateral shift < 10-μm peak-to-peak, wavefront distortion < 63 nm RMS at 40 K, and wavelength range (0.45–20 μm). The Darwin ODL is representative of a future flight mechanism, with all materials and processes used being suitable for flight qualification. Positioning is done with a voice coil down to subnanometer precision. The verification program, including functional testing at 50 K, has been completed successfully. This technology is at TRL 6 (see Fridlund et al. 2008).

Cryocoolers

With the Advanced Cryocooler Technology Development Program (ACTDP), the Terrestrial Planet Finder (TPF) and *JWST* projects have produced development model coolers that have met or exceeded their performance requirements, which are to provide ~30 mW of cooling at 6 K and ~150 mW at 18 K. This demonstrates the approach to cooling the science detector to a temperature low enough to reveal the weak planet signals. This activity is at TRL 6.

Thermal shields

Science requirements for *JWST* have driven the need for a deployable, low areal-density, high thermal-performance efficiency (effective emittance, e* of 10^{-4} to 10^{-5}) sunshield to passively cool the Observatory Telescope Elements and Integrated Science Instruments Module (OTE/ISIM). The thermal performance dictated the need for a sunshield consisting of multiple, space-membrane layers such that the ~200 kW of the Sun's energy impinging on the sun-facing layer would be attenuated such that the heat emitted from the rear or OTE-facing membrane would be < 1 W. This would enable the OTE/ISIM to operate at cryogenic temperature levels (< 40 K) and have a temperature stability of 0.1 to 0.2 K over the field-of-regard pointing re-alignments.

Based on these top-level mission requirements a sunshield was developed employing five membrane layers with pitch and dihedral separation angles of 1.6 and 2 degrees, respectively. The present sunshade design for *JWST* is at TRL 6 and meets the similar requirements for the flagship mission and is more than adequate for a small mission (Kurland 2007).

Detector Technology

Detectors or Sensor Chip Assemblies (SCAs) from the *JWST* Mid-Infrared Instrument (MIRI) have been developed by Raytheon Vision Systems (RVS) having 1024 × 1024 pixels fabricated from arsenic-doped silicon (Si:As) and which consist of a detector layer and a readout multiplexer. The required performance levels are dark current less than 0.03 electrons per second, readout noise less than 19 electrons, and quantum efficiency > 50%. These detectors have been rigorously tested and have met or exceeded these requirements for *JWST*, giving a TRL of 6 (Ressler 2007). These detectors meet or exceed the requirements for both a small structurally connected interferometer mission and the flagship mission.

4. Formation Flying

Guidance, Navigation, and Control

Ground-based simulations and robotic demonstrations of formation flying have shown that the guidance, navigation, and control is feasible. In 2007 the Formation Control Testbed (FCT) at JPL demonstrated precision maneuvers using two robots, showing autonomous initialization, maneuvering, and operation in a collision-free manner. This was the project's Milestone #2. The key maneuver that was demonstrated was representative of TPF-I science observations and the performance of these algorithms was shown to exceed TPF-I flight requirements.

Additional tests that could be carried out with the FCT include demonstrating new capabilities such as (1) reactive collision avoidance, (2) formation fault detection, and (3) autonomous reconfiguration and retargeting maneuvers. Also, using a real-time simulation environment would allow the demonstration of performance with full formation-flight complexity, with five interacting spacecraft showing synchronized rotations, autonomous reconfigurations, fault detection, and collision avoidance. However, the greatest advance in technology readiness would be to test the algorithms in a space environment.

National agencies in Europe are actively advancing the technology of formation flying, with flight missions starting in 2009–2014. The European Space Agency and national space agencies in Europe have a program of precursor missions to gain experience in formation flying. In 2009 the Swedish Space Agency will launch the Prisma mission. This is primarily a rendezvous and docking mission, but it will also test RF metrology designed for Darwin. In 2012 ESA plans to launch Proba-3, which will include optical metrology loops for sub-millimeter range control over a 30-m spacecraft separation.

The opportunity no doubt exists to leverage the expertise developed for TPF-I in collaboration with European colleagues. The greatest advance in maturing technology for formation flying would be to have a modest-scale technology mission devoted to verifying and validating guidance and control algorithms, as well as the interferometric combination of starlight from separated platforms.

A ground-based facility such as the FCT should continue to provide the means to test and improve real-time formation-flying algorithms as the technology matures, even while the technology is being proven in space.

Propulsion Systems

Missions employing Precision Formation Flying (PFF) require propulsion capabilities that exhibit low plume contamination, high thrust precision, and high power and propellant efficiency. Ion thrusters typically deliver low-contamination plumes and high efficiency by using noble gas propellants, but conventional thrusters provide minimum thrust levels over an order of magnitude greater than the sub-milli-Newton (mN) to mN levels needed for precision-controlled formation-flying space interferometer missions.

The Miniature Xenon Ion (MiXI) thruster developed at JPL, would satisfy mission requirements. One particularly useful characteristic of the MiXI thruster is its incredibly large thrust range that provides smooth amplitude modulated thrust in the 0.1–3.0 mN in the amplitude-modulated mode and 0.001–0.1 mN of thrust in pulse-width modulation (PWM) mode (patent-pending). With a minimum on-time of less than 1 ms, the MiXI thruster can provide impulse bits of less than 1 μN·s at low power levels. The PWM mode of the MiXI thruster is achieved by precision control of the thruster voltages.

A program of testing these thrusters using microsatellites would provide confidence that the technology is ready for a larger mission.

5. Conclusions

The technology program for the Terrestrial Planet Finder Interferometer has made remarkable progress in the past decade. The project is now close to achieving all of its current milestones in starlight suppression. The basic component technology for starlight suppression at mid-infrared wavelengths is now at TRL 4. TRL 5 requires testing in a relevant environment, which for TPF/Darwin would be a cryogenic vacuum near 50 K. Most research so far has been undertaken in air at room temperature. Sufficient progress has now been made that the greatest advance in this area would be to proceed to cryogenic brass-board designs of already successful components and subsystems, and to implement system-level cryogenic testing.

Ground-based demonstrations with the Formation Control Testbed (FCT) have shown that the Guidance, Navigation, and Control algorithms now exist to execute precision maneuvers with two telescopes (Scharf & Lawson 2008). Additional testing should be carried out to validate collision avoidance and fault tolerant algorithms, but the greatest advance would be to transition to space-based demonstrations in collaboration with our European colleagues.

A vigorous technology program, including component development, integrated testbeds, and end-to-end modeling, should be carried out in the areas of formation flying and mid-infrared nulling, with the goal of enabling a flagship mission within the next 10 to 15 years.

The fruitful collaboration with European groups on mission concepts and relevant technology should be continued.

We request funding at the level of $300M in the 2010–2020 decade to bring cryogenic nulling technology to TRL 6, and enable an international collaboration in space-based precision formation flying, bringing formation flying technology to TRL 9.

6. Web Links and Related Milestone Documents

A broader overview of the technology for mid-IR interferometry and formation flying can be found at the following website:
http://planetquest.jpl.nasa.gov/TPF-I/

Milestone #1 (Completed)
R. D. Peters, O. P. Lay, and M. Jeganathan, "Broadband phase and intensity compensation with a deformable mirror for an interferometric nuller," Appl. Opt. 47, 3920 (2008).
http://www.opticsinfobase.org/ao/abstract.cfm?uri=ao-47-21-3920

Milestone #2 (Completed)
"TPF-I Technology Milestone #2 Report: Formation Control Performance Demonstration," Edited by D.P. Scharf and P. R. Lawson, JPL Pub. 08-11 (January 2008).
http://planetquest.jpl.nasa.gov/TPF-I/TPFI_M2_ReportV3.pdf

Milestone #3 (Completed)
"Exoplanet Interferometry Technology Milestone #3 Report: Broadband starlight suppression demonstration," Edited by R. D. Peters, R. O. Gappinger, P. R. Lawson, and O. P. Lay, JPL Document D-60326 (February 2009).
http://planetquest.jpl.nasa.gov/TPF-I/TPF-I_M3_Report_023_small.pdf

Milestone #4: Whitepaper (In Progress)
"Exoplanet Interferometer Technology Milestone #4 Whitepaper: Planet Detection Demonstration," Edited by S. R. Martin, A. J. Booth, O. P. Lay and P. R. Lawson, "(May 2008).
http://planetquest.jpl.nasa.gov/TPF-I/TPF-I_M4_Whitepaper_Final.pdf

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