Jet Propulsion Laboratory
California Institute of Technology

TERRESTRIAL PLANET FINDER INTERFEROMETER

TECHNOLOGY MILESTONE #1 WHITE PAPER

AMPLITUDE AND PHASE CONTROL DEMONSTRATION

December 18, 2006

TERRESTRIAL PLANET FINDER INTERFEROMETER

TECHNOLOGY MILESTONE #1 WHITE PAPER

Approvals

Prepared By:

Peter Lawson
Dec 18, 2006

Peter Lawson,
TPF-I Systems Manager

Date

Approved By:

Daniel Coulter
12/18/2006

Daniel Coulter,
TPF Project Manager

Date

Charles Beichman
12/18/06

Charles Beichman,
TPF-I Project Scientist

Date

Michael Devirian
12/20/2006

Michael Devirian,
Navigator Program Manager

Date

Z. Tsvetanov
01/11/2007

Zlatan Tsvetanov
TPF Program Scientist

Date

Lia S. LaP
1/16/2007

Lia LaPiana,
TPF Program Executive

Date

TPF-I Technology Milestone #1 White Paper: Amplitude and Phase Control Demonstration

1. Objective

In support of the Terrestrial Planet Finder Interferometer (TPF-I) pre-phase-A development program, this white paper explains the purpose of TPF-I Technology Milestone #1, specifies the methodology for computing the milestone metric, and establishes the success criteria against which the metric will be evaluated.

2. Introduction: Adaptive Nuller

Full spectral, quasi-static control of intensity and phase of interfering beams for deep, broadband nulls.

This technology milestone was established in the TPF-I Technology Plan (JPL Pub. 05-5, June 2005) to gauge the developmental progress of the TPF-I project and its readiness to proceed from pre-Phase A to Phase A. Completion of this milestone is to be documented by the project, reviewed by the EIRB, and approved by NASA HQ. The Adaptive Nuller milestone described here addresses amplitude and phase control. It is discussed in the Technology Plan and reads as follows.

> **Milestone #1: Dispersion Control**
>
> Using the Adaptive Nuller**,** demonstrate that optical beam amplitude can be controlled with a precision of $\leq$ 0.2% rms and phase with a precision of $\leq$ 5 nm rms over a spectral bandwidth of > 3 μm in the mid IR for two polarizations. This demonstrates the approach for compensating for optical imperfections that create instrument noise that can mask planet signals. *Milestone TRL 4.*

The variations in amplitude and phase that may be present across a broad wavelength band make nulling extremely challenging. The Adaptive Nuller is designed to correct these variations, matching the intensity and phase between the two arms of the interferometer, as a function of wavelength, for each linear polarization. The flight requirements and testbed goals are summarized in Table 1. The Adaptive Nuller allows high performance nulling interferometry, while at the same time substantially relaxing the requirements on the nulling interferometer's optical components.

All designs under consideration for TFP-I include a single-mode spatial filter through which the combined light is passed before being detected. The wavefront from the star is incident on the collecting apertures of the instrument and delivered by the respective beam trains to a central beam combiner that couples the combined light into a single-mode filter. With just a single mode for each polarization state, the problem of nulling the on-axis light is simplified. Higher order wavefront aberrations that would reduce the visibility of the fringes (depth of the null) are rejected by the spatial filter. Small errors in tilt in each arm of the interferometer thus translate into small errors in received intensity. The adaptive nuller is not designed to adjust wavefront errors across each pupil, as these are rejected independently by the spatial filter. The adaptive nuller technology demonstration only addresses wavelength and polarization dependent amplitude and phase errors. For further information about the mid-infrared spatial filters to be used with TPF-I, the interested reader is referred to Ksendzov *et al*. (2006).

Table 1. Comparison of Current Flight Requirements with Pre-Phase A Nulling Testbed Requirements

Parameter	Flight Performance	Achromatic Nuller	Planet Detection Testbed	Adaptive Nuller
Null depth	7.5×10^{-7}	1×10^{-6}	1×10^{-6}	1×10^{-5}
Amplitude control	0.13%	Derived	0.12%	0.2% (static)
Phase control	1.5 nm	Derived	2 nm	5 nm (static)
Stability timescale	50,000 s +	100 s	5,000 s	6 h
Bandwidth	7–17 μm	25%	λ = 10.6 μm	30 %

The adaptive nuller uses a deformable mirror to adjust amplitude and phase independently within the single mode filter in each of about 12 spectral channels. A schematic of the adaptive nuller is shown in Fig. 1, as it would be used to adjust the intensity and phase of one beam in a two-beam nuller. The incident beam is first split into its two linear polarization components, and also divided into roughly a dozen spectral channels. These beams are then directed onto a deformable mirror, where the piston of each pixel independently adjusts the phase of each channel. Tilt in the orthogonal direction may also be independently adjusted, and, by means of controlled vignetting at a subsequent aperture, provides an independent adjustment of the intensity in each channel. The various component beams are recombined to yield an output beam that has been carefully tuned for intensity and phase in each polarization as a function of wavelength. If the adaptive nuller is used to balance beams entering a nulling interferometer, matching tolerances on optical components in that interferometer are substantially relaxed. Ultimate null depth and stability are now determined by the performance of the adaptive nuller, under active control that can be monitored (see Sections 3.1.6 and 3.1.8c) and readily characterized, and optical components need only be of sufficient quality that the two arms of the interferometer are matched in intensity and phase to within the capture range of the Adaptive Nuller.

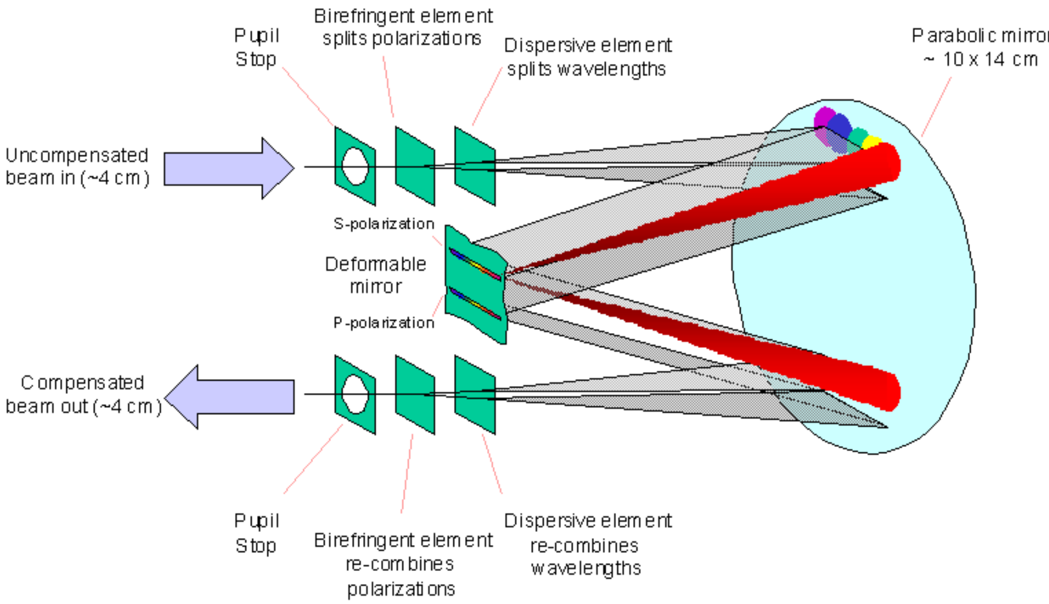

Figure 1. Schematic of the Adaptive Nuller. Light in one arm of a nulling interferometer is balanced by splitting it into component polarizations and wavelength channels, then individually adjusting the phases in each channel with a deformable mirror prior to recombining both polarizations. Further details of the design are described by Peters *et al.* (2006).

The principal investigator of the Adaptive Nuller is Robert Peters at the Jet Propulsion Laboratory.

A visible/near-infrared proof-of-concept experiment was completed as the first stage of this development effort. The proof-of-concept was done with null depth requirements that were relaxed due to the lab conditions, and the amplitude control was scaled to the wavelength and beam size used. This test exceeded its performance target of 5% and 15 nm, achieving intensity control to 2% and phase control to 2 nm. This represented the state of the art, as there had been no previous capability demonstrated in this area.

The adaptive nuller will use a broadband thermal source to generate light with a spectral width > 3 µm in the 7–12 µm wavelength band. This light will be put through a simple interferometer with one arm holding the adaptive nuller components, and the other serving as a reference arm. There will be intensity and phase dispersion in this interferometer due to normal manufacturing tolerances as well as intentionally added optical material in one arm.

We will measure the intensity dispersion as a function of intensity difference between the arms of the interferometer versus wavelength. From this measurement, we will calculate the adjustments needed to the deformable mirror actuator and apply the correction. We will then re-measure the intensity dispersion and show that it is corrected to $\leq$ 0.2% rms (1 σ) intensity difference between the arms.

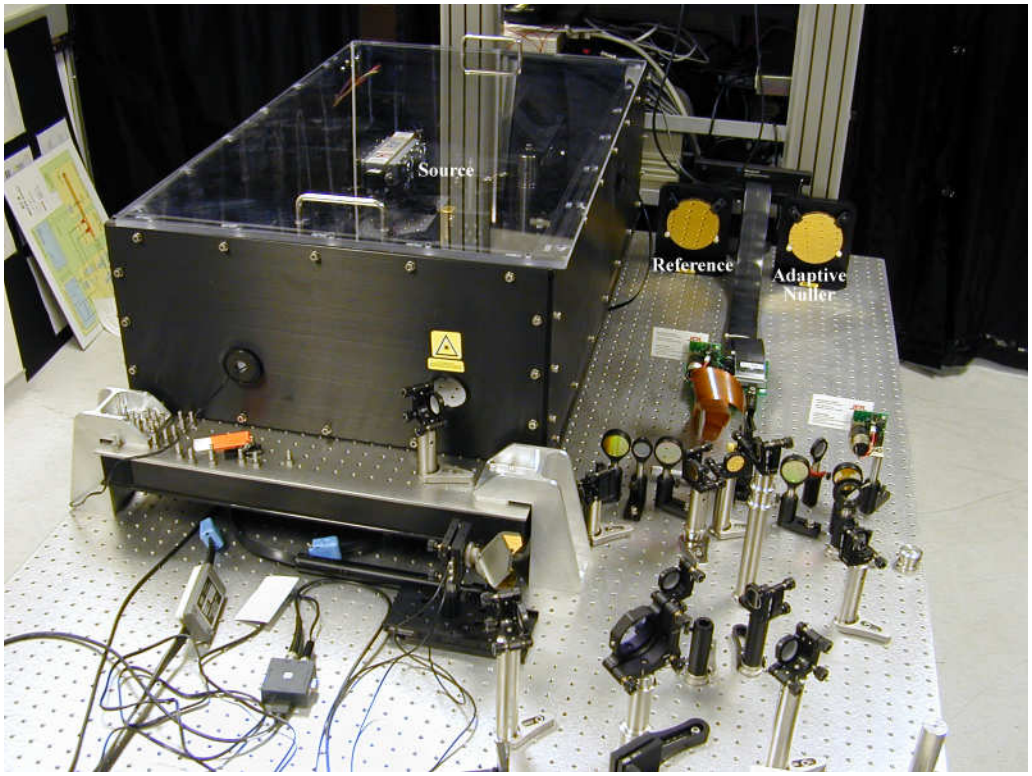

Figure 2. Experimental Layout for a Mid-Infrared Adaptive Nuller showing the source, reference arm, and adaptive nuller arm of the interferometer.

We will measure the phase dispersion as a function of residual phase difference between the arms of the interferometer versus wavelength. As with the intensity dispersion, this information is used to apply the proper correction to the deformable mirror actuator. The phase dispersion will be measured again to show that it is corrected to $\leq$ 5nm rms (1 σ) phase dispersion.

The tests outlined in this document are performed in the mid-IR, but without independent control of each polarization. Although Wollaston prisms are included in the design, there are no Wollaston prisms in the mid-IR testbed. The polarization is selected at the source and only one polarization is treated to compensate for intensity and phase. The testbed results are for one polarization only, because if one polarization can be compensated, then it would be straightforward to compensate *both* using the same overall approach. It is simply a matter of cost. At mid-IR wavelengths, the only material that can be used to make a Wollaston prism is cadmium selenide (CdSe). As this is a very expensive material to manufacture for optical components, the Adaptive Nuller was first built to control the two polarizations independently at *near-IR* wavelengths using quartz Wollaston prisms that are relatively inexpensive. This test showed that the concept would also work at mid-IR wavelengths. We nonetheless developed and tested a Zemax model for the performance of a CdSe Wollaston prism to operate in the mid-IR. Thus for this mid-IR demonstration, the polarization is selected at the source, and there are no Wollaston prisms in the experiment. This simplification in the layout does not detract from the importance of these results.

3. Computation of the Metric

3.1. Definitions

The TPF-I Adaptive Nuller M1 amplitude and phase control demonstration requires measurement and control of amplitude dispersion and phase dispersion in an interferometer. In the following paragraphs we define the terms involved in this process, spell out the measurement steps, and specify the data products.

3.1.1. "Star". We define the "star" to be a 75 μm diameter pinhole illuminated with ceramic heater thermal source with a temperature of 1250–1570 K. This "star" is the only source of light in the optical path of the adaptive nuller. It is a stand-in for the star signal that would have been collected by the telescope systems in TPF-I; however it is not intended to simulate any particular collector design or expected flux.

3.1.2. "Dispersion". We define dispersion to be the difference in either amplitude or phase as a function of wavelength between the two arms of an interferometer.

3.1.3. "Algorithm". We define the "algorithm" to be the computer code that takes as input the measured amplitude and calculated phase dispersion, and produces as output a voltage value to be applied to each element of the DM, with the goal of reducing the dispersion.

3.1.4. **"Cross coupling"**. We define cross coupling to be the unintended adjustment of phase while amplitude is being corrected or the unintended adjustment of amplitude while phase is being corrected.

3.1.5. **"Dispersion free source"**. We define a dispersion free source to be a carbon dioxide laser with narrow spectral line width that is co-aligned with the "star" source. As we are only able to control dispersion, we do not expect to achieve a null deeper than the null obtained with this source.

3.1.6. **"Active metrology"**. We define active metrology as a system which uses a laser at 1.3 μm wavelength to measure the difference in optical paths of the two arms of the interferometer. This information is then fed back to the delay line control to maintain a set path difference.

3.1.7. "Spectrometer". We define a spectrometer to be a device to measure intensity as a function of wavelength. The device consists of a grating to disperse the incoming light. The dispersed light is then focused by an off-axis parabola onto a linear mercury cadmium telluride array with 16 elements. Each element produces a voltage proportional to the intensity in a wavelength range selected by the grating. The output voltages are then sent through a multiplexer to a lock-in amplifier with an integration time set from 100 ms to 1 s depending on the signal level. The output of the lock-in amplifier is then read by the computer for each element of the linear array. Noise may be reduced by averaging up to 10 frames taken from the spectrometer.

3.1.8. "**Adaptive nulling"**. We define the process of adaptive nulling to be the following 4 step process, iteratively repeated for as many cycles as necessary to reach the desired level of amplitude and phase dispersion.
a) Measure the amplitude dispersion in the interferometer by measuring the intensity spectrum of each arm independently while shuttering off the other arm.
b) Compute the required tilts to equalize the amplitude difference in each channel of the deformable mirror (DM) and apply these voltages.
c) Calculate the phase dispersion in the interferometer by actuating the delay line several fringes off the null and measuring the dispersed spectral fringes with the spectrometer and applying an algorithm to the output.
d) Compute the required pistons to equalize the path lengths in each channel of the DM and apply these voltages.

3.2. Measurement of the null

Each null measurement is obtained as follows:

3.2.1. The delay line is actuated by the computer to locate the approximate position of the minimum integrated power as measured on the spectrometer.

3.2.2. The delay line is then actuated by the computer to the peak integrated power. The set point is slowly scanned on the active metrology to locate the peak. The peak integrated power is used to normalize the null depth.

3.2.3. The delay line is then actuated by the computer back to the null.

3.2.4. The metrology set point is then slowly scanned by the computer to find the minimum integrated power as measured on the spectrometer.

3.2.5. The active metrology system can then be used to hold this position to measure the time evolution of the null.

3.3. Adaptive Nuller Milestone 1 Validation Demonstration Procedure

3.3.1. All DM actuators are set to half their control range.

3.3.2. The active metrology system and the star are turned on. The delay line is then actuated by the computer to locate the null position.

3.3.3. An initial uncorrected null is measured as described in Sec. 3.2.

3.3.4. The delay line is actuated away from the null by several fringes and adaptive nulling is performed to correct the measured amplitude dispersion to ≤0.2% and correct the measured phase dispersion to ≤5nm.

3.3.5. The delay line is actuated by the computer to locate the null position.

3.3.6. The corrected null is measured as described in Sec. 3.2

3.3.7. The delay line is actuated by the computer several fringes from the null and the phase dispersion is calculated and amplitude dispersion is measured.

3.3.8. To measure the stability, step 3.3.6 is repeated while the DM voltages are held constant and the active metrology holds the delay line position to measure the time evolution of the null.

3.3.9. Step 3.3.7 is repeated while the DM voltages are held constant. Active metrology then holds the delay line position during the phase calculation to measure the time evolution of the phase and amplitude dispersion.

3.3.10. The source is switched from the star to the dispersion free source and the amplitudes in each arm of the interferometer are matched.

3.3.11. A dispersion free null is measured as described in Sec. 3.2.

3.3.12. The following data are to be archived for future reference: (a) raw spectrometer output of null and peak of star before and after correction, (b) phase and amplitude dispersion before and after correction, (c) raw spectrometer output of the null and peak, and phase and amplitude dispersion measured at each time interval after correction, (d) raw null and peak data for the dispersion free source.

3.3.13. The following data are to be presented in the final report: (a) Plot showing peak and null as a function of wavelength before and after correction, (b) plot of time series with RMS and P-V phase and amplitude dispersion, (c) plot of time series of null depth, (d) null depth of dispersion free source, (e) throughput of the adaptive nuller arm of the interferometer measured with the dispersion free source.

3.3.14. Repeat steps 3.3.1 – 3.3.13 on two more occasions on different days, with at least two days between each demonstration.

4. Success Criteria

The following is a statement of the 6 elements that must be demonstrated to close the TPF-I Adaptive Nuller M1. Each element includes a brief rationale.

4.1 An amplitude dispersion corrected to $\leq 0.2\%$ rms (1σ) over a bandwidth > 3 µm in the 7–12 µm wavelength range starting with a mean error as a function of wavelength of at least 9% between the two arms of the interferometer.

Rationale: *This provides evidence that a wavelength dependent amplitude mismatch can be corrected, which cannot be done through traditional methods.*

4.2 A phase dispersion corrected to ≤ 5 nm rms (1σ) over a bandwidth of > 3 µm in the 7–12 µm wavelength range starting with a mean error as a function of wavelength of at least 400nm between the two arms of the interferometer.

Rationale: *This provides evidence that the wavelength dependent phase mismatch can be corrected.*

4.3 Both (4.1) and (4.2) are to be satisfied simultaneously after iterating between amplitude and phase correction.

Rationale: *This provides evidence that the cross coupling will not limit the ability to achieve the requirement.*

4.4 A peak rejection ratio with the star that is within 10% of the peak rejection ratio of the dispersion free source at each spectral channel.

Rationale: *The dispersion free source tests the fundamental limit of the interferometer's performance. Adaptive nulling only compensates polarization-dependent amplitude and phase dispersion; therefore, other factors such as path length fluctuations that may limit the peak rejection ratio should be common to both the corrected star and dispersion free source.*

4.5 A time series showing deviation of the amplitude and phase to be within the ranges defined in (4.1) and (4.2) for a 6 hour period while the DM control voltages are held constant. As was done in the proof-of-concept demonstration, room temperature will be monitored but not controlled beyond the facility controls for the room.

Rationale: *The adaptive nuller is a quasi-static correction that cannot be changed during an observation. Therefore, the system must remain stable during the rotation of the array.*

4.6 Elements 4.1 – 4.5 must be satisfied on three separate occasions with at least two days in between each demonstration.

Rationale: *This provides evidence of the repeatability of the adaptive nuller.*

5. Certification Process

The TPF-I Project will assemble a milestone certification data package for review by the EIRB. In the event of determination that the success criteria have been met, the project will submit the finding of the review board, together with the certification data package, to NASA HQ for official certification of milestone compliance. In the event of disagreement between the project and the EIRB, NASA HQ will determine whether to accept the data package and certify compliance or request additional work.

5.1. Milestone 1 Certification Data Package

The milestone certification data package will contain the following explanations, charts, and data products.

5.1.1. A narrative report, including a discussion of how each element of the milestone was met, an explanation of each plot or group of plots, appropriate tables and summary charts, and a narrative summary of the overall milestone achievement.

6. References

Robert D. Peters, Oliver P. Lay, Akiko Hirai, Muthu Jeganathan, "Adaptive nulling for the Terrestrial Planet Finder Interferometer," in *Advances in Stellar Interferometry*, J. D. Monnier, M. Schöller, and W. C. Danchi, Editors, Proc. SPIE **6268**, 62681C (2006).

A. Ksendzov, E. Bloemhof, V. White, J. K. Wallace, R. O. Gappinger, J. S. Sanghera, L. E. Busse, W. J. Kim, P. C. Pureza, V. Q. Nguyen, I. D. Aggarwal, S. Shalem, and A. Katzir, "Measurement of spatial filtering capabilities of single mode infrared fibers," in *Advances in Stellar Interferometry*, J. D. Monnier, M. Schöller, and W. C. Danchi, Editors, Proc. SPIE **6268**, 626838 (2006).

P. R. Lawson and J. A. Dooley, Editors, Technology Plan for the Terrestrial Planet Finder Interferometer, JPL Pub 05-5 (Jet Propulsion Laboratory: Pasadena, CA, 2005). http://planetquest.jpl.nasa.gov/Navigator/library/tpfI414.pdf

Some of the research described in this (publication or paper) was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.