National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

TPF Terrestrial Planet Finder

Terrestrial Planet Finder Interferometer Technology Status and Plans

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J.K. Wallace, B. Ware

2:00 pm, Tuesday, 30 May 2006

The Navigator Program

Exploring New Worlds

TPF Terrestrial Planet Finder

Navigator Program Prime Objective

Advanced telescope searches for Extrasolar Planets and habitable environments.

- Primary Goals

— Detect and characterize Earth-like exo-planets
— Understand the formation, history and distribution of planetary systems in our Galaxy.

- Secondary Goal

— Understanding of the formation and evolution of stars, planets and galaxies.

KECK

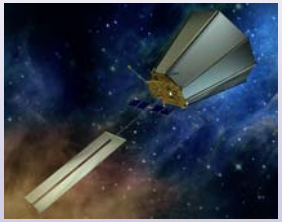
- Characterize inner exo-zodiacal dust environments
- Identify long-period planets, "warm-Jupiters"

LBTI

- Characterize outer dust environments
- Observe giant planets

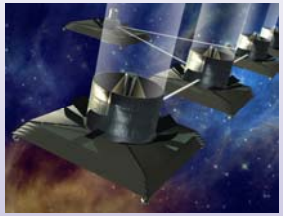
SIM PlanetQuest

- Search for terrestrial planets
- Characterize planetary systems
- Determine planet mass



TPF-C

- Detect Earth-like planets in visible light
- Characterize planet atmospheres
- Assess habitability



TPF-I

- Detect Earth-like planets in infrared light
- Characterize planet atmospheres
- Search for indicators of life

Michelson Science Center

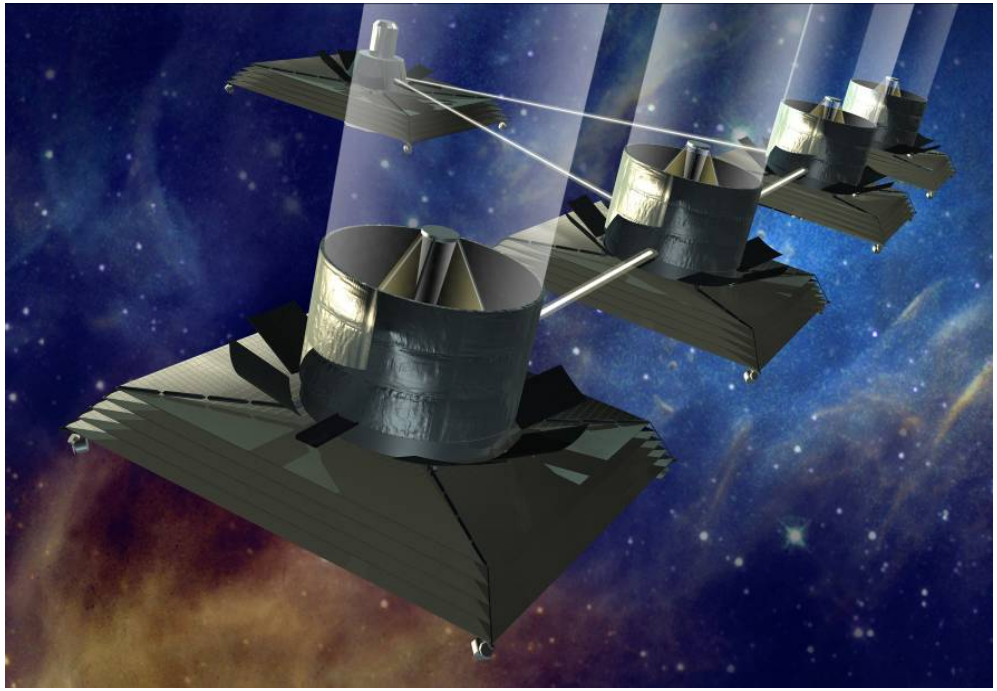
- Science community development
- Science operations for Navigation missions
- Multi-mission tools and science data archives to support Navigation Program projects and science community.

TPF-I Project Overview

TPF Terrestrial Planet Finder

Salient Features

- Formation Flying Mid-IR nulling Interferometer
- Starlight suppression to 10^{-6} (mid-IR)
- Heavy class launch vehicle
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency's Darwin Mission



Science Goals

- Detect any Earth-like planets in the "habitable zone" of nearby stars via their reflected light or thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, albedo, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as O_2, O_3, CO_2, CH_4 and H_2O
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics as capability and time allow

Project Organization

TPF Terrestrial Planet Finder

TPF Office
Manager; Dan Coulter
Project Engineer: Richard Key
Project Resource Admin: Sherry Casson
Project Secretary; David Bui

- **Industry Support** — Allan Eisenman
  - Ball (Noecker)
  - NGST (Lillie)
  - LMMS (Pitman)
- **Science Office** — Steve Unwin
  - Interferometer (Serabyn/Beichman)
  - Coronagraph (Staplefeldt/Traub)
  - STDT/ISWG
  - GSFC (Danchi/Heap)
- **Coronagraph (733)** — Marie Levine, PEM; Wes Traub, Proj. Sci.
  - Arch/Model/Sim (Shaklen/Levine)
  - HCIT (Kuhnert/Trauger)
  - Masks/Stops (Balasubramanian)
  - TDM (Cohen)
  - Universities (Eisenman) (UofHI, UCB, Princeton)
- **Interferometer (734)** — Peter Lawson, PEM; Chas Beichman, Proj. Sci
  - Arch/Model/Sim (Lay/Ware)
  - Nulling
    - ANT (Wallace)
    - PDT (Martin)
    - Adaptive Nuller (Peters)
    - Spatial Filters (Ksendzov)
  - Formation Flying (Hadaegh/Ahmed)
  - Universities (Eisenman) Common Path Phasing (UofA)

Technology Plan for TPF-I

Technology Plan for the Terrestrial Planet Finder Interferometer

JPL Pub 05-5, June 2005

Edited by P.R. Lawson and J.A. Dooley

http://tpf.jpl.nasa.gov

- Requirements and Error Budgets
- Technology Development Strategy
- Testbed descriptions
- Technology Milestones

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TPF-I Testbeds

- Formation Control Testbed
  - Hardware and real-time control algorithms
- 10 micron nulling testbeds
  - Achromatic Nulling Testbed (deep nulls, 20% bandwidth)
  - Planet Detection Testbed (null stability and control)
  - Adaptive Nuller (amplitude and phase control)
  - Common-path Phase Sensing Testbed
- Mid-IR single mode fiber optics
  - Chalcogenide fibers from Naval Research Labs
  - Silver halide fibers from University of Tel Aviv
  - Testing of higher-order mode suppression at JPL

Nulling Error Budget

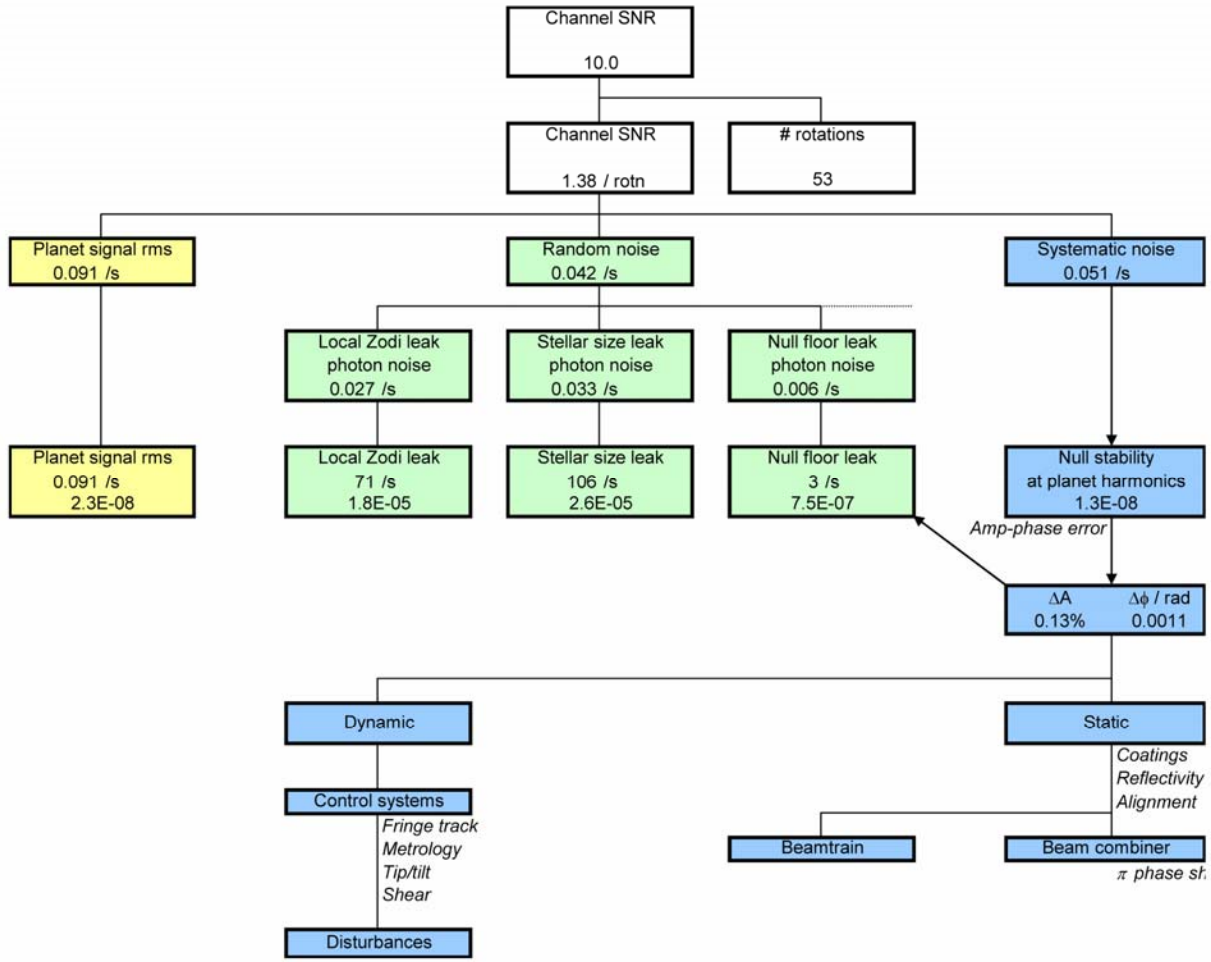

Figure 2-5. Simplified TPF-I Error Budget for the Signal-to-Noise Ratio Required for Ozone Detection at 10-µm Wavelength

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Nulling Testbeds

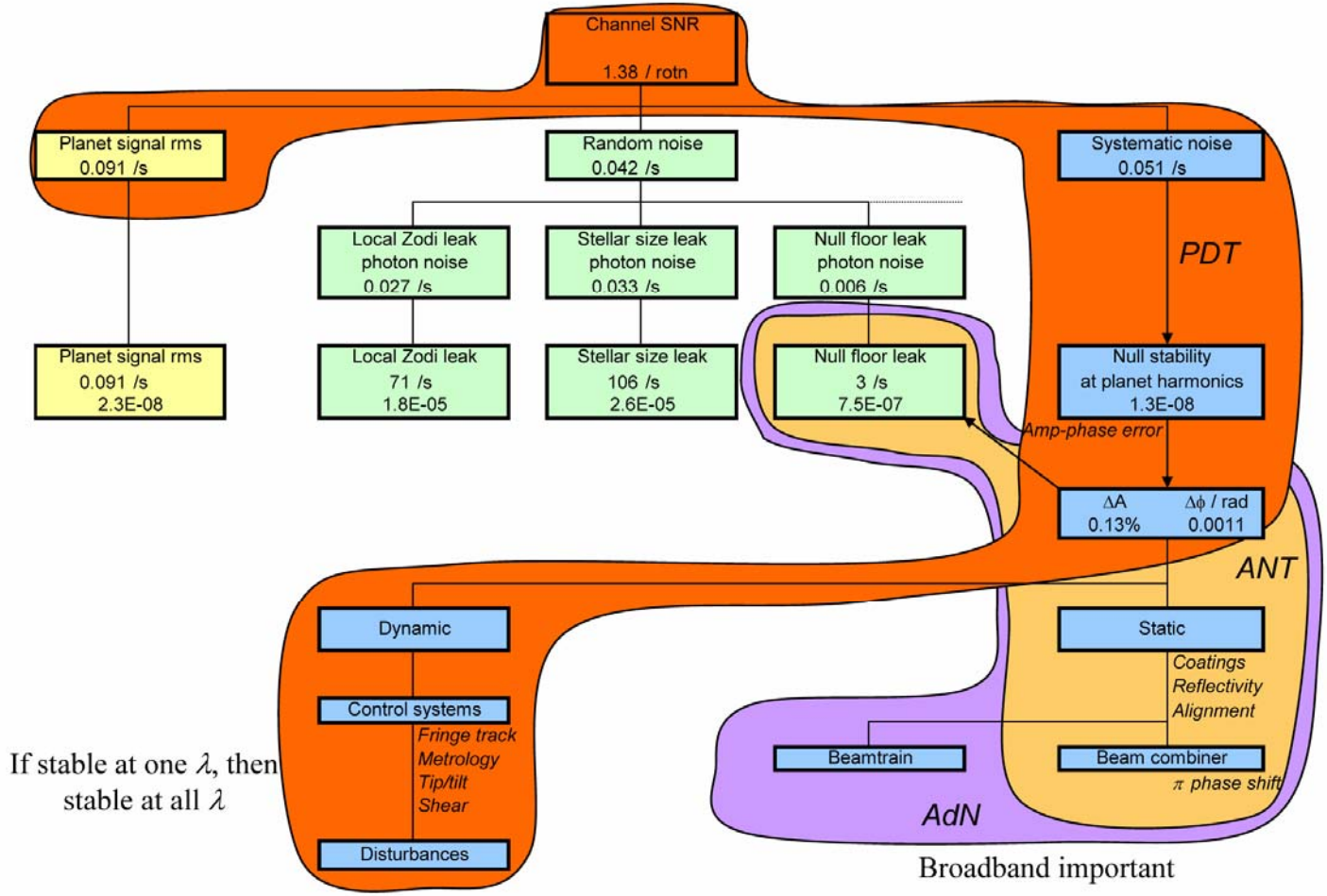

Figure 2-6. Relationship Between the Achromatic Nulling Testbed (ANT), Adaptive Nuller (AdN), and Planet Detection Testbed (PDT) with the Simplified TPF-I Error Budget

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Nulling Requirements

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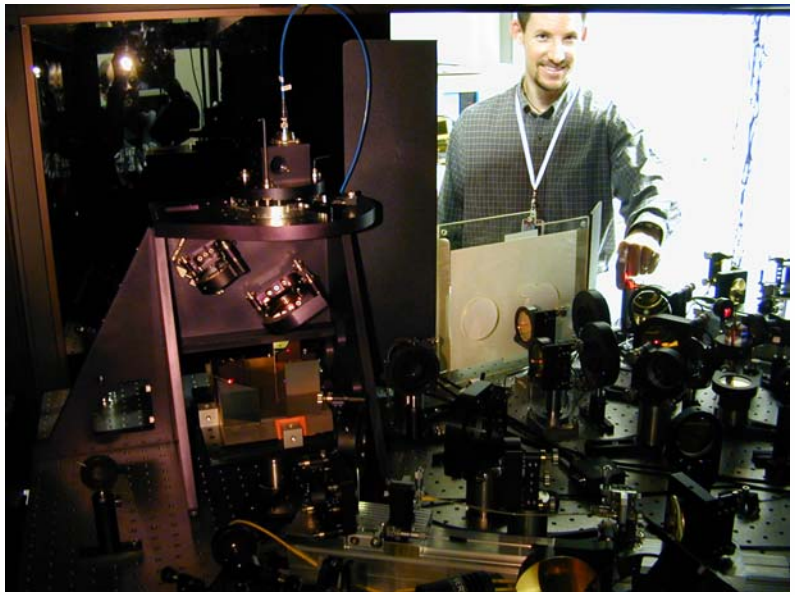
Table 2-1. Comparison of Current Flight Requirements with Pre-Phase A Nulling Testbed Requirements

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%	0.1% (static)
Phase control	1.5 nm	Derived	2 nm	1 nm (static)
Stability timescale	50,000 s +	100 s	5,000 s	100 s
Bandwidth	7–17 μm	25%	$\lambda = 10.6$ μm	6–12 μm

Achromatic Nulling Testbed

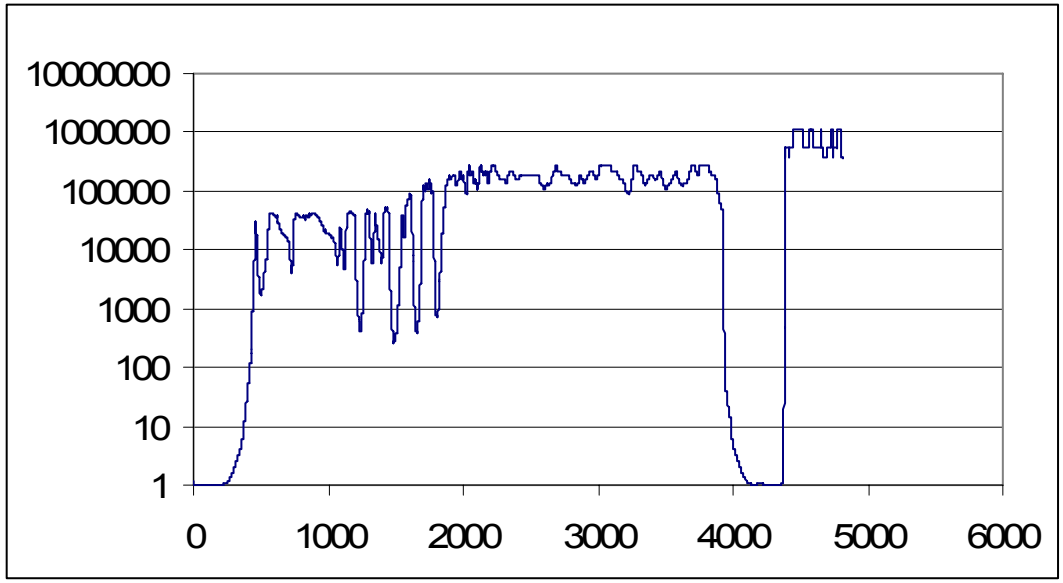


Periscope Nuller is focus of efforts

- Primary source of performance limitation has now been identified
- Re-alignment strategy currently under review for August milestone

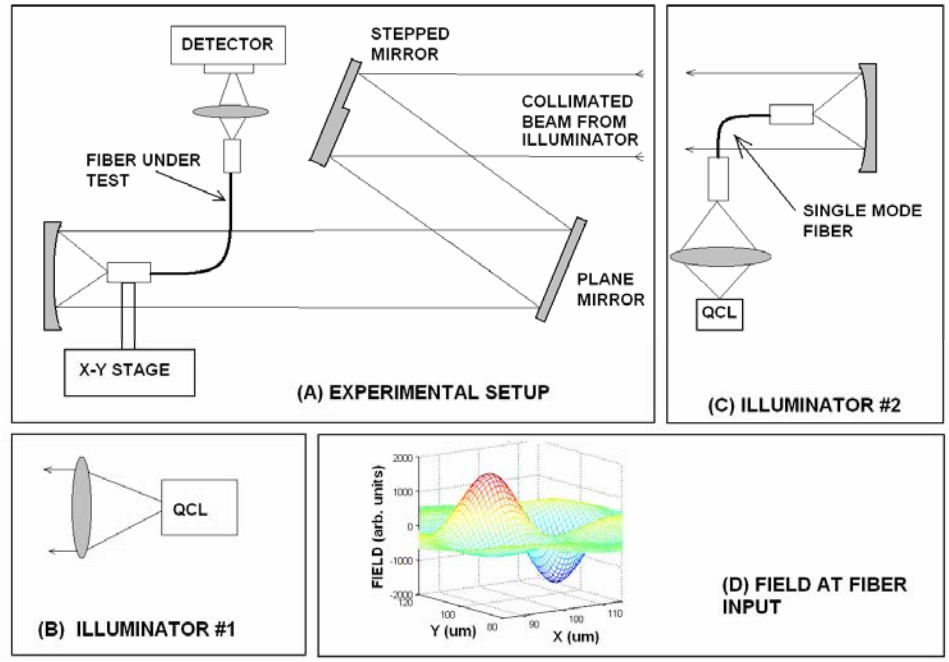
Best performance to date

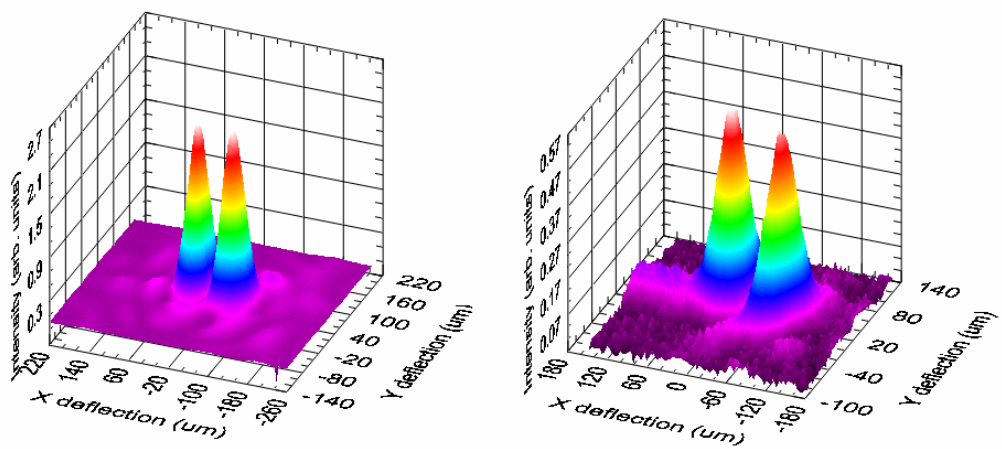
- 200,000:1 null achieved in 10 µm **laser** light
- 15,000:1 nulls at 25% bandwidth



Single Mode Spatial Filter Technology

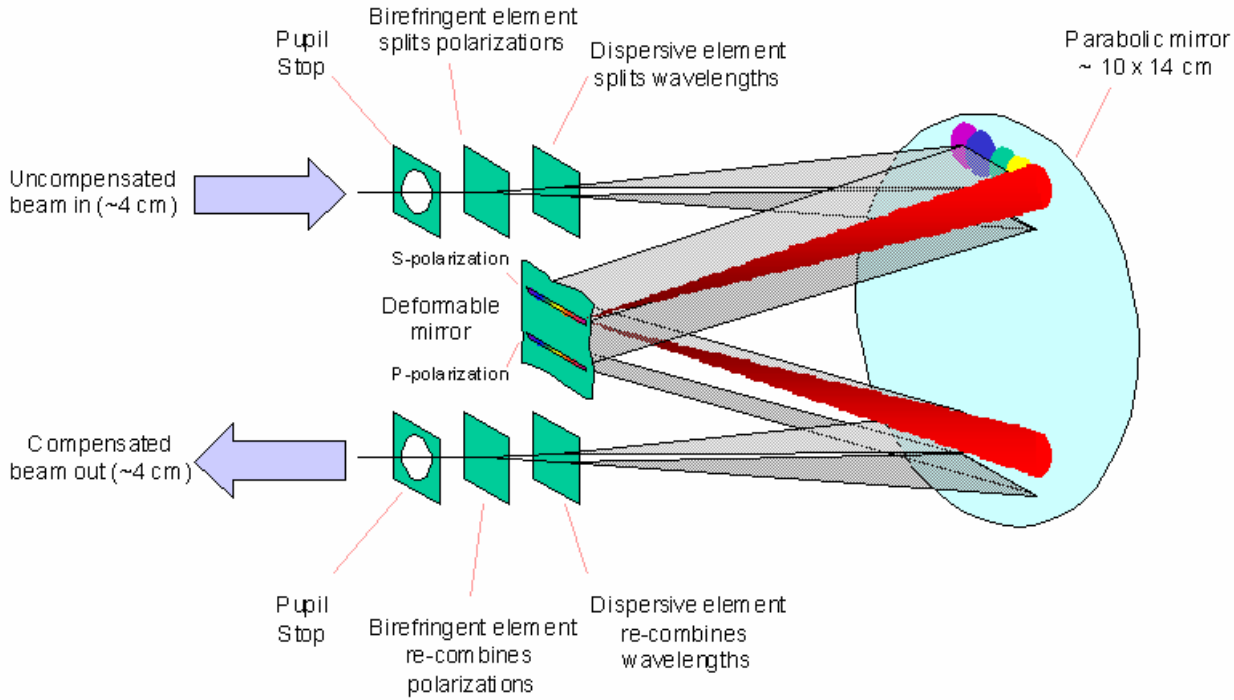
- Received a new shipment of fibers from Tel Aviv University (TAU)
- Reached an agreement with TAU on shipment of packaged (connectorized) fibers
- Obtained publication-quality data on one TAU and one NRL fiber
- Submitted paper to SPIE; collecting additional data for refereed journal paper
- Established the measurement and the numerical procedure for determining the fiber performance
- Conclusions: presumed leakage mechanism is through the cladding modes. Leakage is ~6×10^{-6} for both fibers.





Scan of fiber through the focal plane. (A): NRL and (B): TAU

Adaptive Nuller Testbed



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*. (2004).

- Corrects for amplitude and phase as a function of wavelength
- Demonstrated intensity control to 2% and phase control to 2 nm over wavelengths 800 to 900 nm.
- Under development for 8-12 micron range: control to 0.2% and 5 nm.

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TPF-I: Planet Detection Testbed (PDT)

Planet detection at 10µm with phase modulation

- < 1×10^{-5} mean null depth
- Chopping of the planet signals at the thermal source
- Star/planet contrast
  - Faint planet = 4×10^{-7}
  - Bright planet = 1.5×10^{-6}

Phase modulation results from August 2005 reproduce amplitude modulation performance achieved in June.

Stability and phase-chopping milestones upcoming in 2006.

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Planet Detection Testbed

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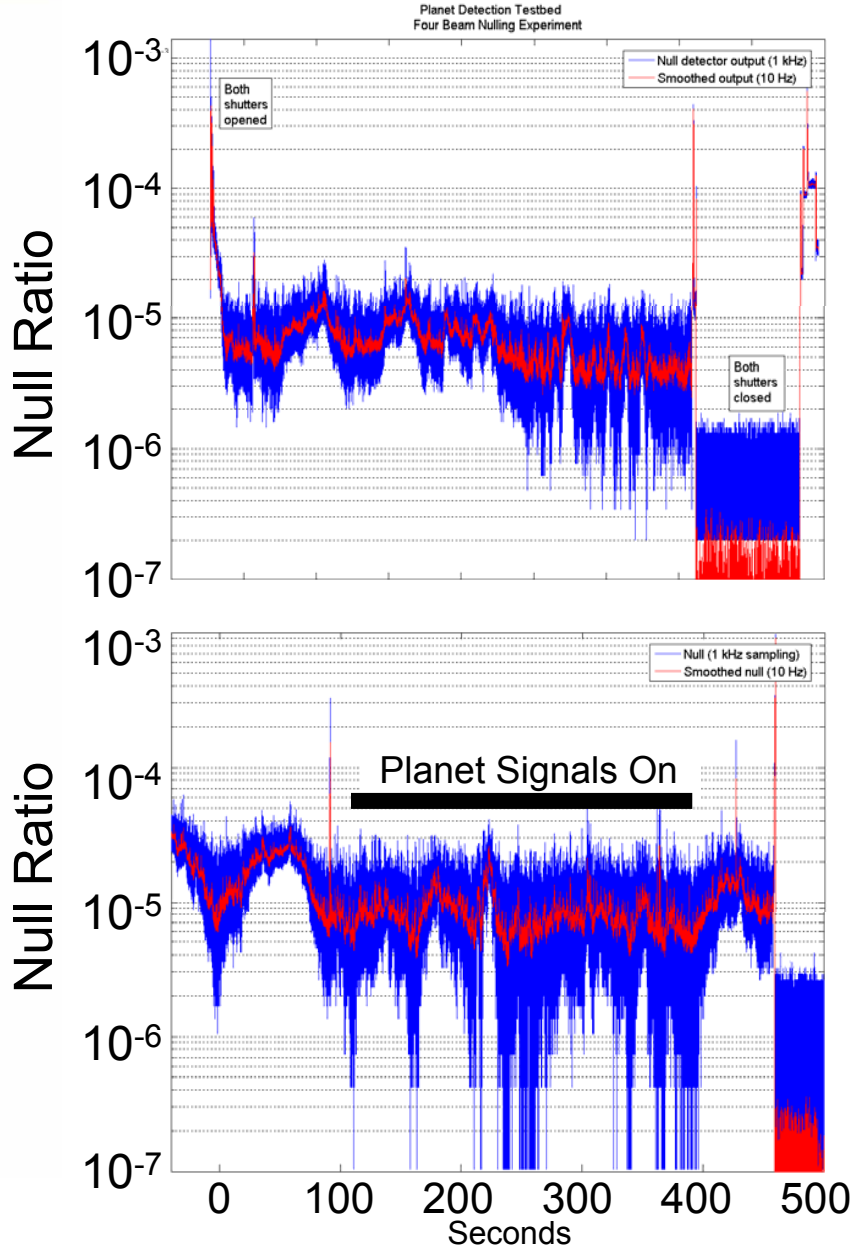
Four beam nulling @ 10 µm

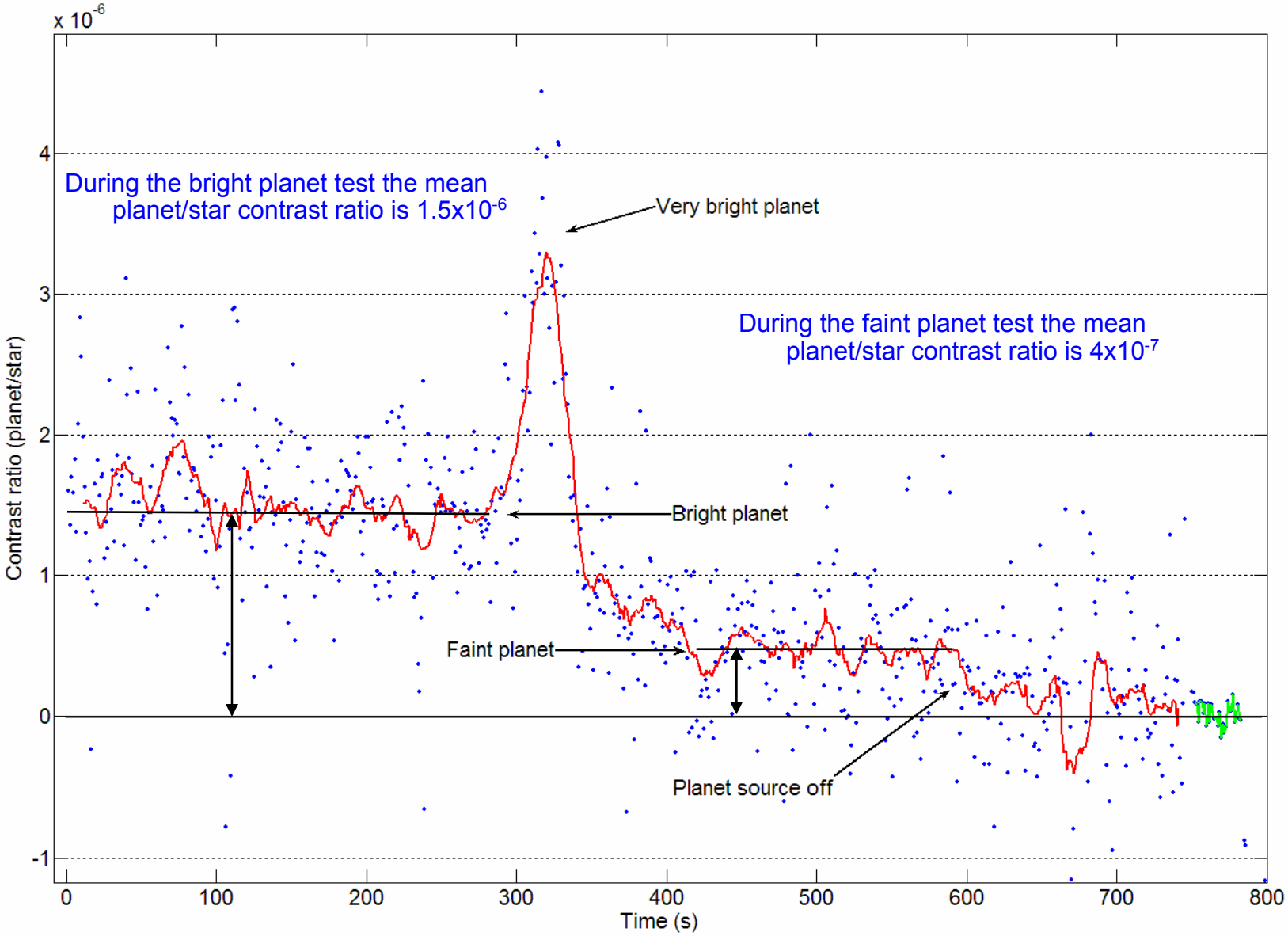
- > 100,000:1 mean null depth
- > 10 minutes
- Four control loops dithering the nulls
- Noise floor is detector limited

Planet detection at 10µm

- > 100,000:1 mean null depth
- > 10 minutes
- Amplitude chopping of the planet signals at the thermal source
- Star/planet contrast
  - Faint planet = 2,000,000:1
  - Bright planet = 510,000:1



Planet Detection Testbed Phase Modulation Experiment



Formation Control Testbed

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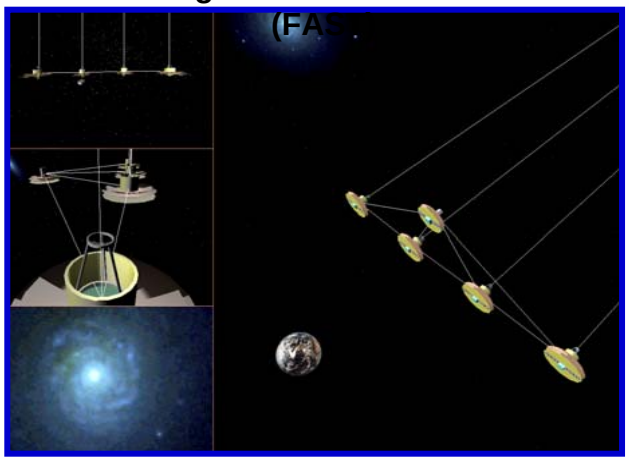
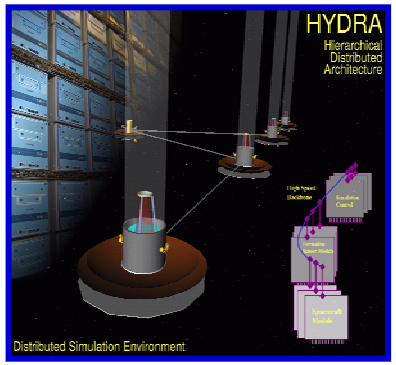
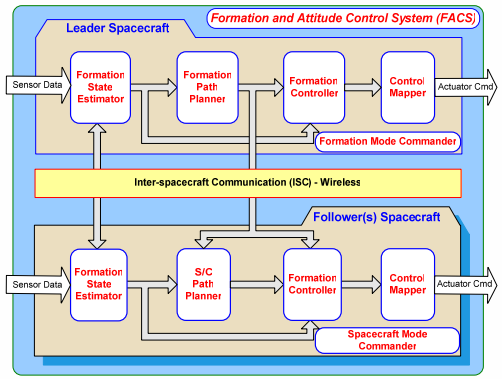
Formation Algorithm & Simulation Testbed (FAST)



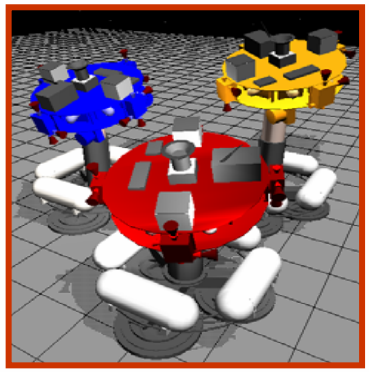
Formation Control Testbed (FCT)



Distributed Realtime Simulation Architecture



Formation Flying Control Architecture



Ground Testbed Performance Simulation

- **Achieved Formation Control of FCT Robots with FF S/W Controlling the two robots using the wireless Inter-Spacecraft Communication (ISC), Timing, and Synchronization functions**
- **Formation Software to Robots H/W I&T**
  - **Integrated FF Inter-Spacecraft Communication (ISC) software** (new capability)
  - **Integrated Inter-S/C Clock Timing and Synchronization software** (new capability)

Formation Control Testbed

- R1 commissioned in September 2004
- R2 delivered and tested in January 2006
- All hardware and software upgrades are complete
- Testing in formation mode is ongoing

Acknowledgments

- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.