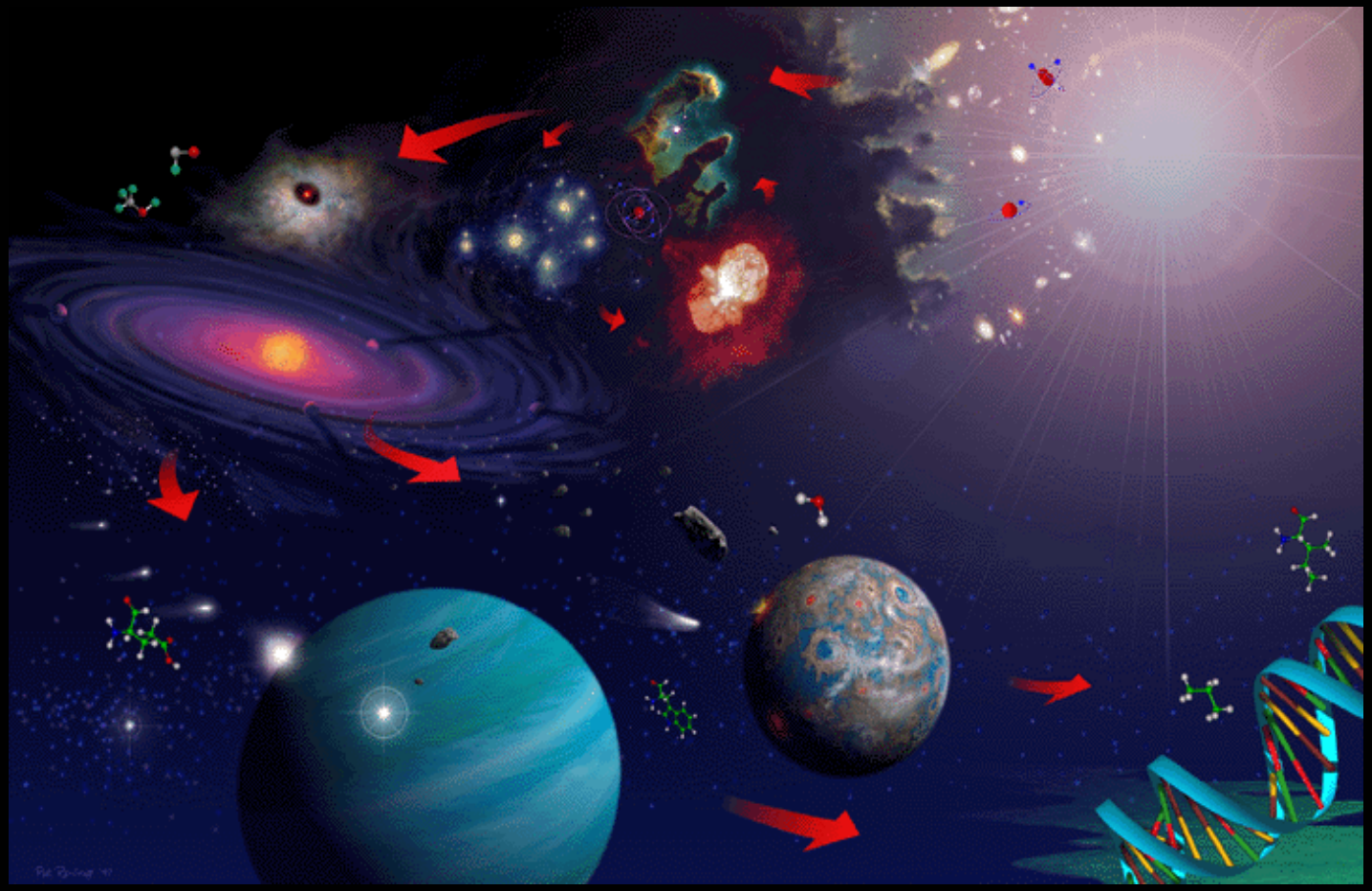
Technology for Space-Based Direct Detection of Terrestrial Planets

Terrestrial Planet Finder Mission

TPF



Jennifer Dooley, JPL

August 30, 2005

A NASA Origins Mission

Outline

- *Introduction to TPF*
- *TPF-C project overview*
- *Technology development*
  - *Masks and stops*
  - *Technology demonstration mirror*
  - *Deformable mirrors*
  - *Coatings*
  - *HCIT*
- *Technology development roadmap*

Terrestrial Planet Finder Science Objectives

- *Primary Goal*: Direct detection of *emitted* or *reflected* radiation from Earth-like planets located in the habitable zones of nearby solar type stars.
  - Determine orbital and physical properties
  - Characterize atmospheres and search for bio-markers
  - Search a statistically meaningful sample of stars (~150)

- *The Broader Scientific Context*: Comparative Planetology
  - Understand properties of all planetary system constituents, e.g. gas giant planets, terrestrial planets and debris disks

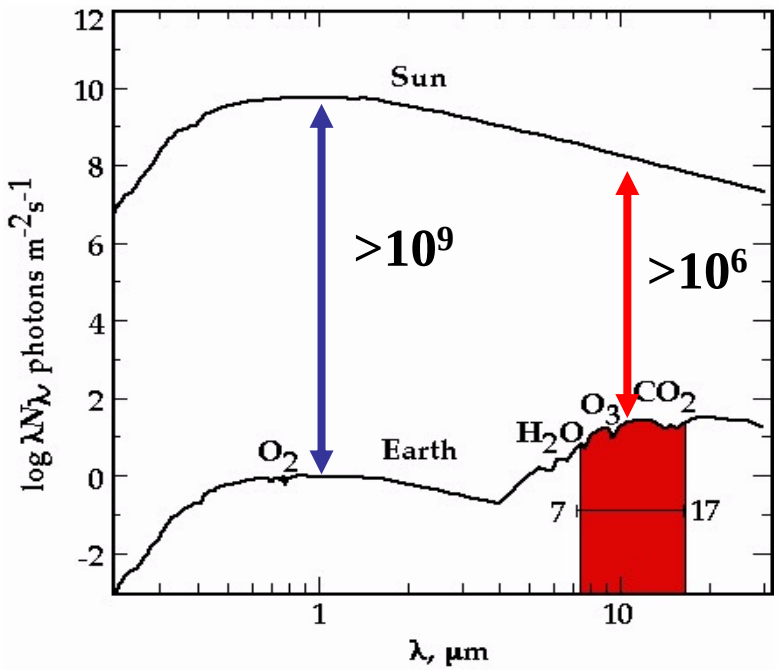
- *Astrophysics:* An observatory with the power to detect an Earth orbiting a nearby star will be able to collect important new data on many targets of general astrophysical interest.

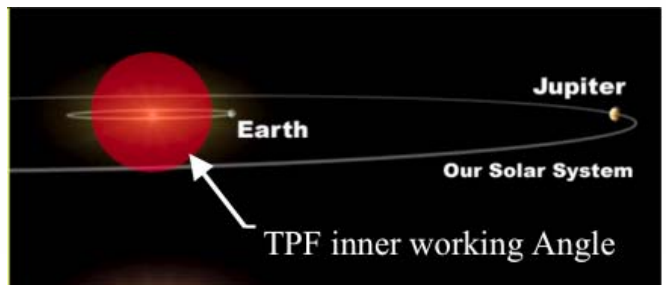
TPF Terrestrial Planet Finder

Detecting Terrestrial Planets

Detecting light from planets beyond solar system is hard:

- Planet signal is weak but detectable (few photons/sec/m$^{2)}$
- Star emits million to billion more than planet
- Planet within 1 AU of star
- Dust in target solar system ×300 brighter than planet





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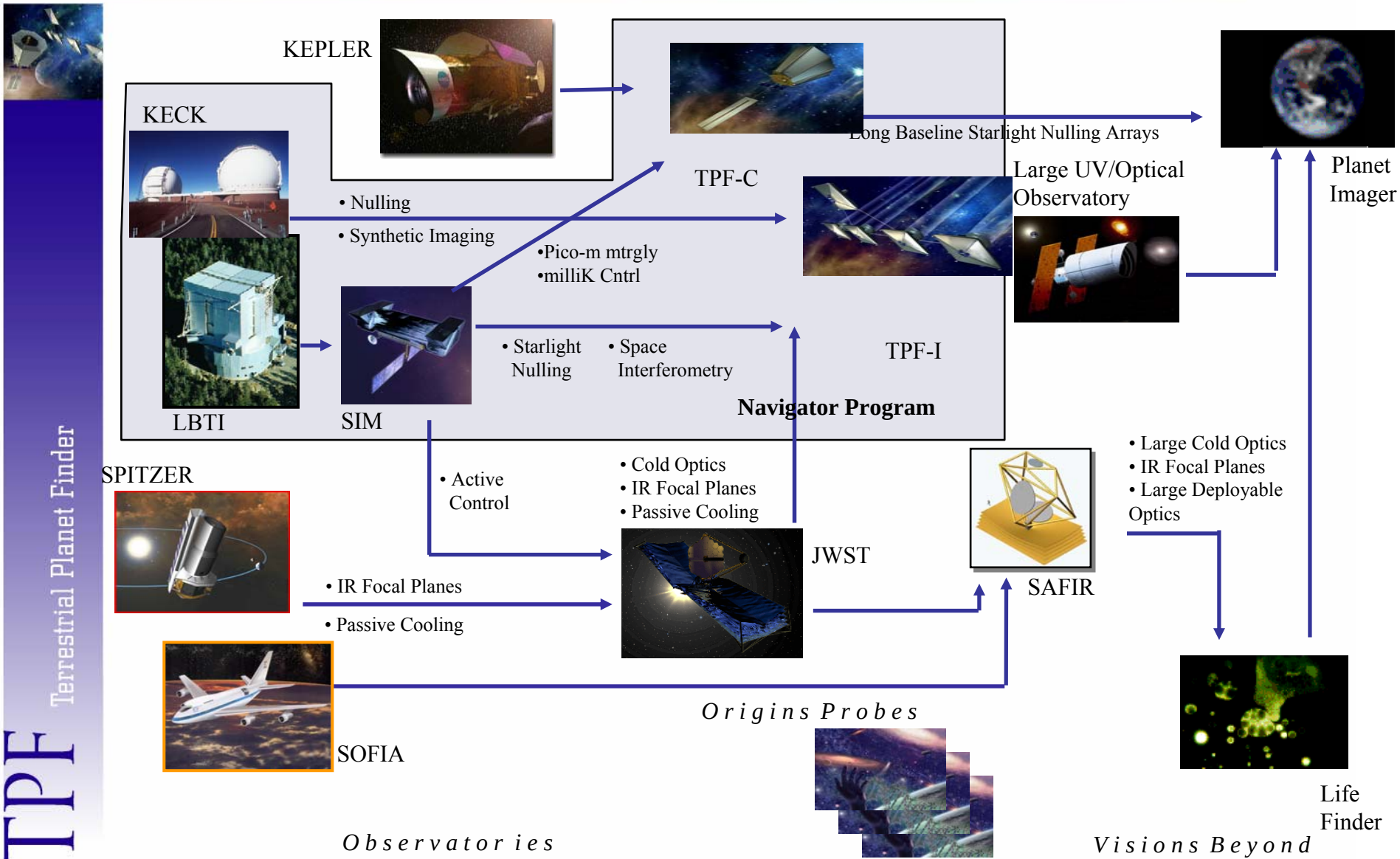
ORIGINS Implementation Roadmap

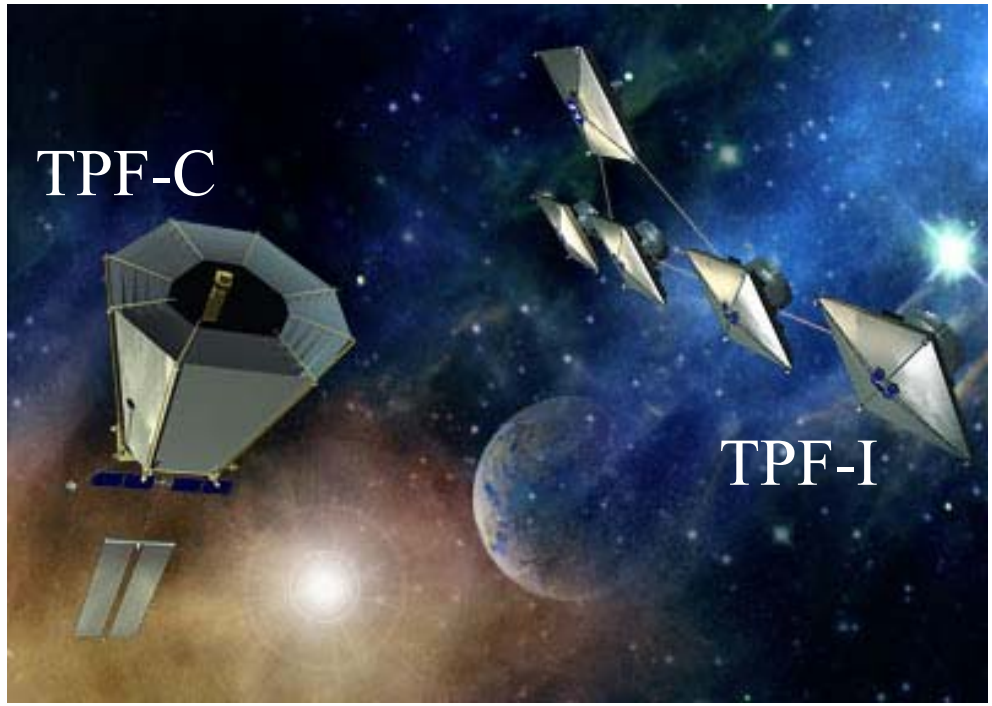


Project Overview

TPF Terrestrial Planet Finder

Salient Features

- Two flight missions
- Visible-NIR Coronagraph and Formation Flying Mid-IR nulling Interferometer
- Starlight suppression to 10^{-10} (vis) and 10^{-6} (mid-IR)
- Heavy class launch vehicles
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency DARWIN Mission on the Formation Flying Interferometer

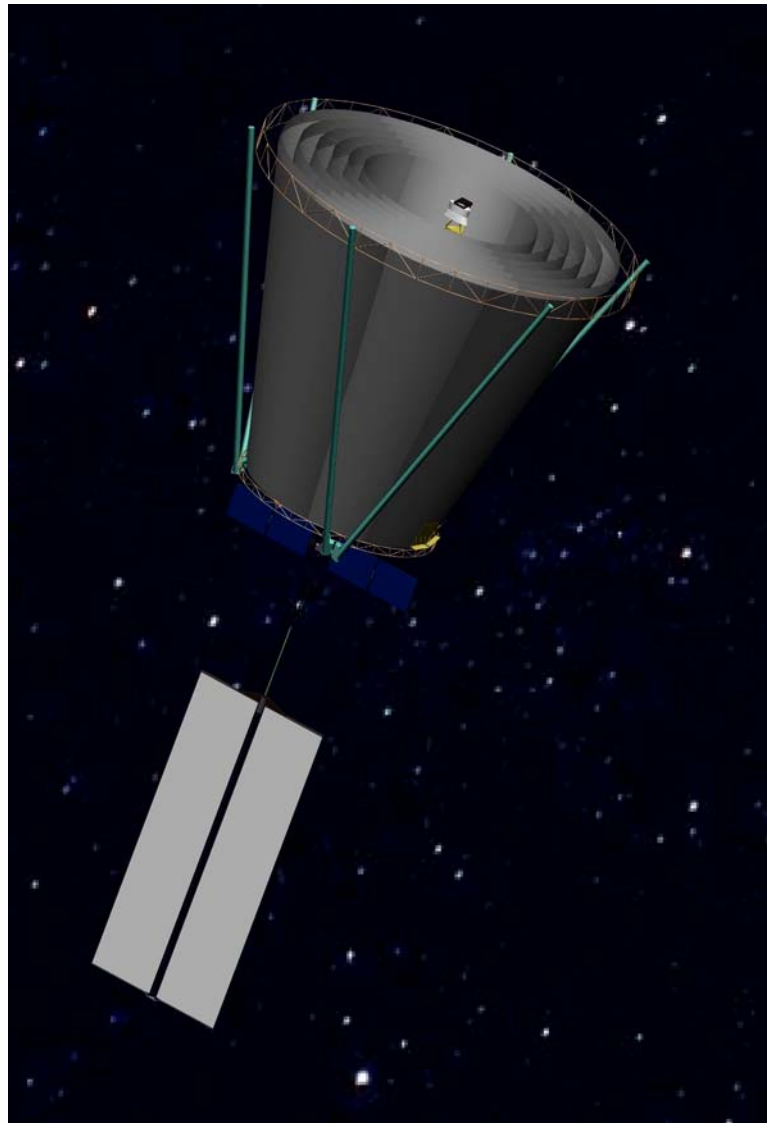


Science Goals

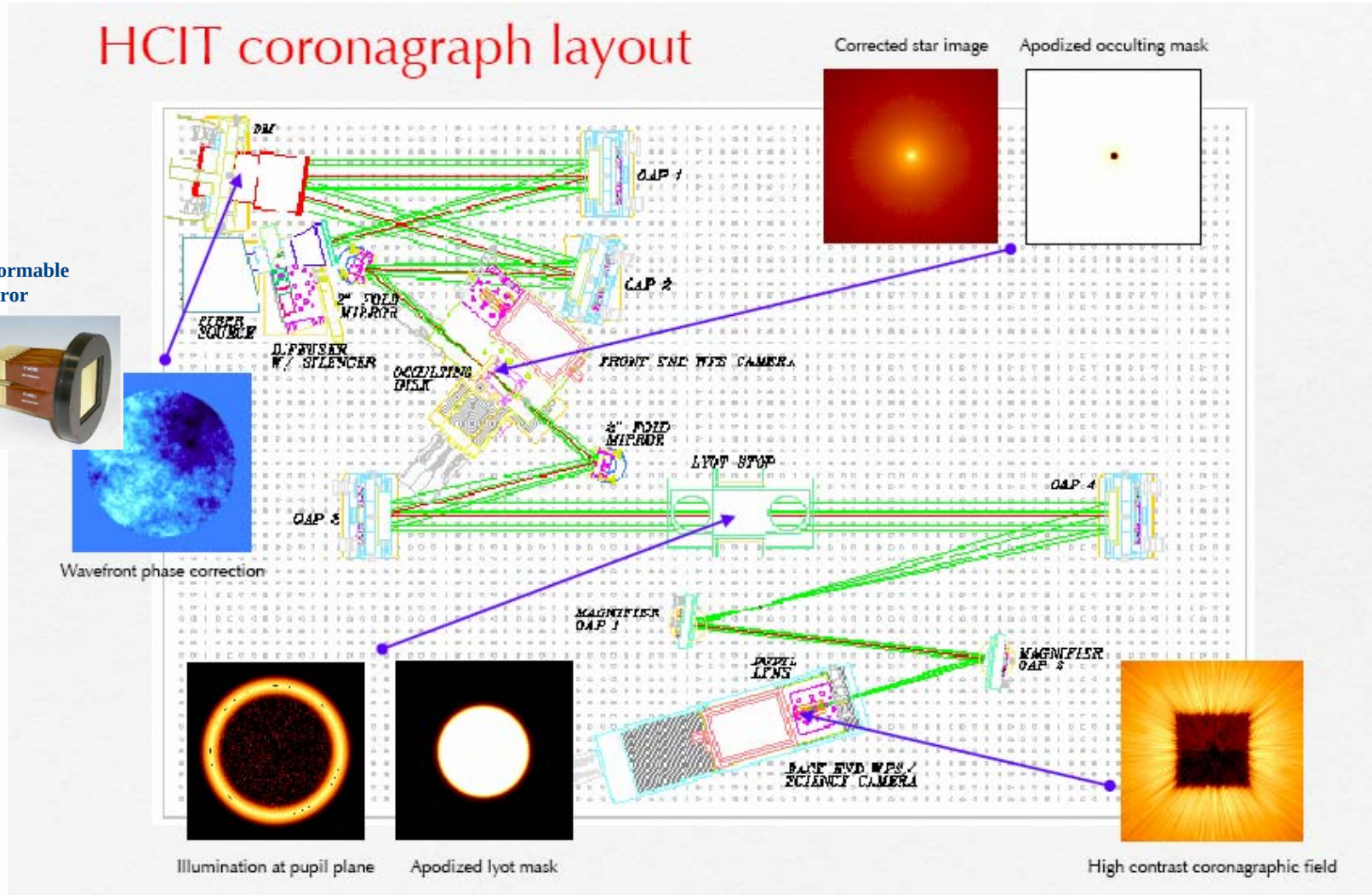
- Detect any Earth-like planets in the “habitable zone” of nearby stars via their reflected light or thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, albedo, presence of atmosphere) and make low resolution spectral observations looking for 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

TPF Terrestrial Planet Finder

TPF Coronagraph



High Contrast Imaging Testbed



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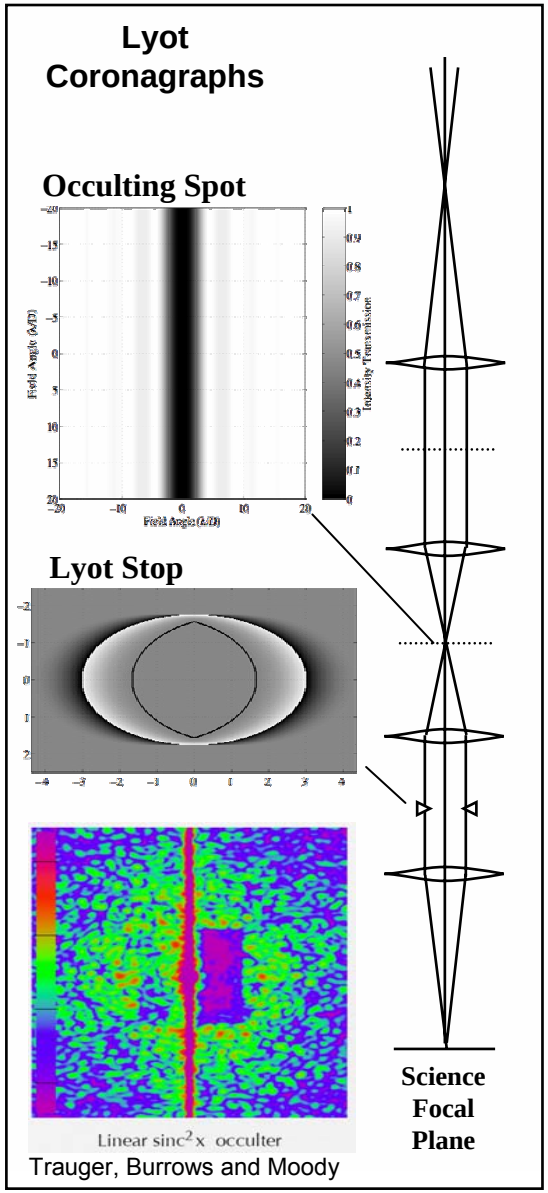
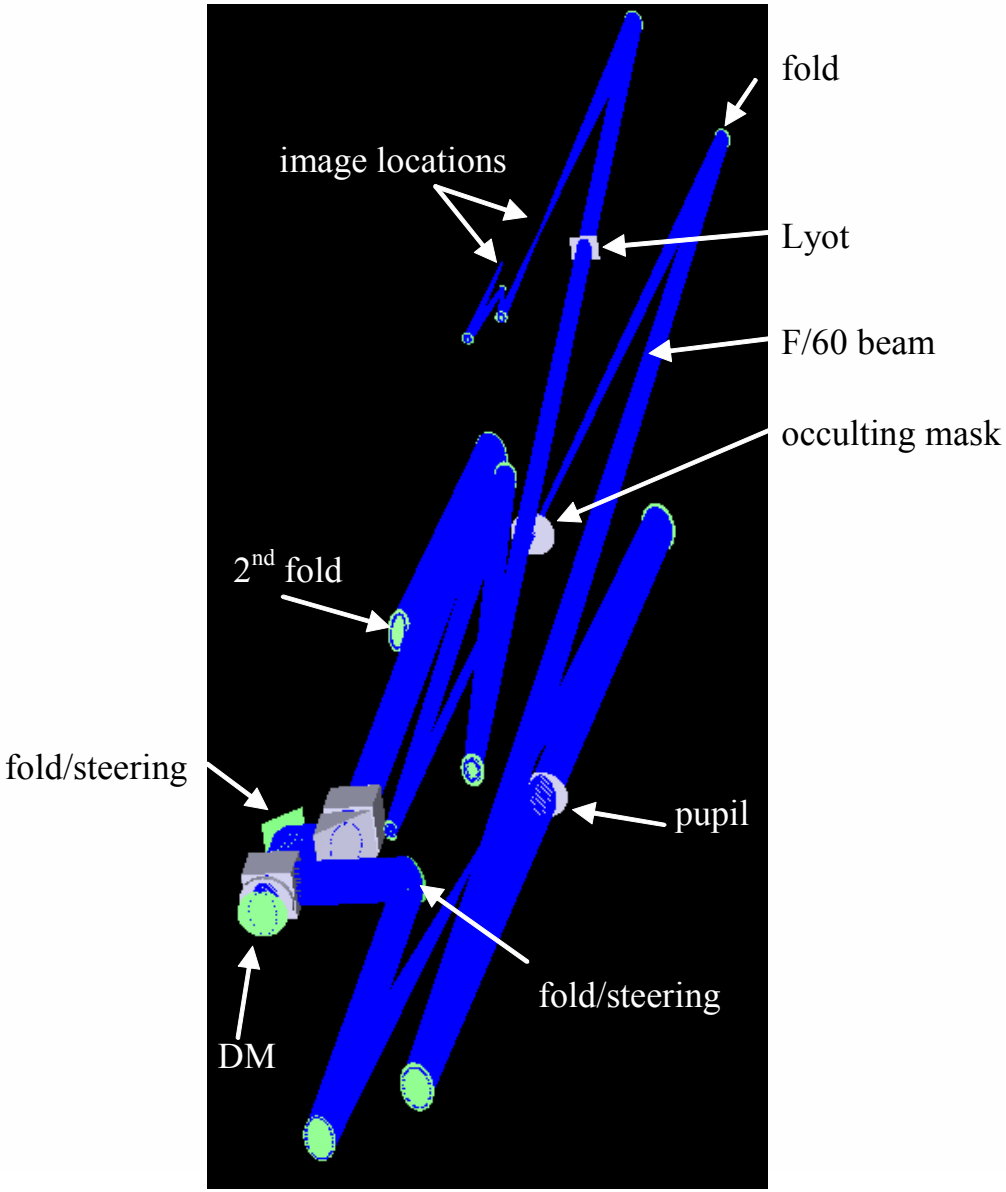
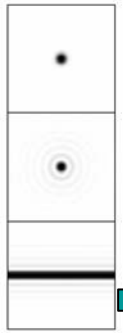
Baseline Lyot Coronagraph



Trauger, Burrows and Moody

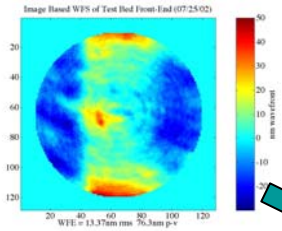


Coronagraph Technology



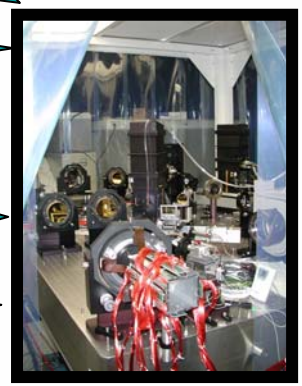
Apodized Masks and Stops Technology

Masks Characterization



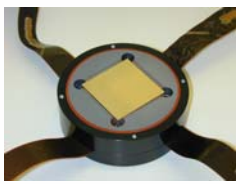
Wavefront Sensing and Control Technology

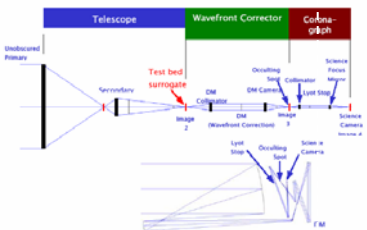
High Contrast Imaging Testbed

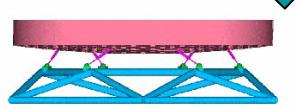


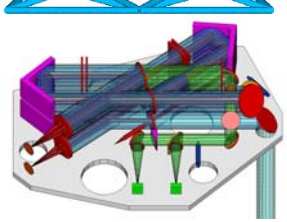
Tools for Integrated Modeling

Industry Coronagraph Technology

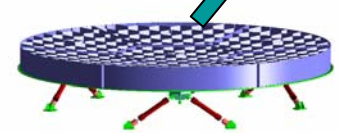






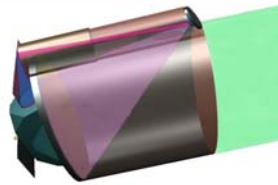


Advanced Coronagraph Technology



Technology Demonstrator Mirror

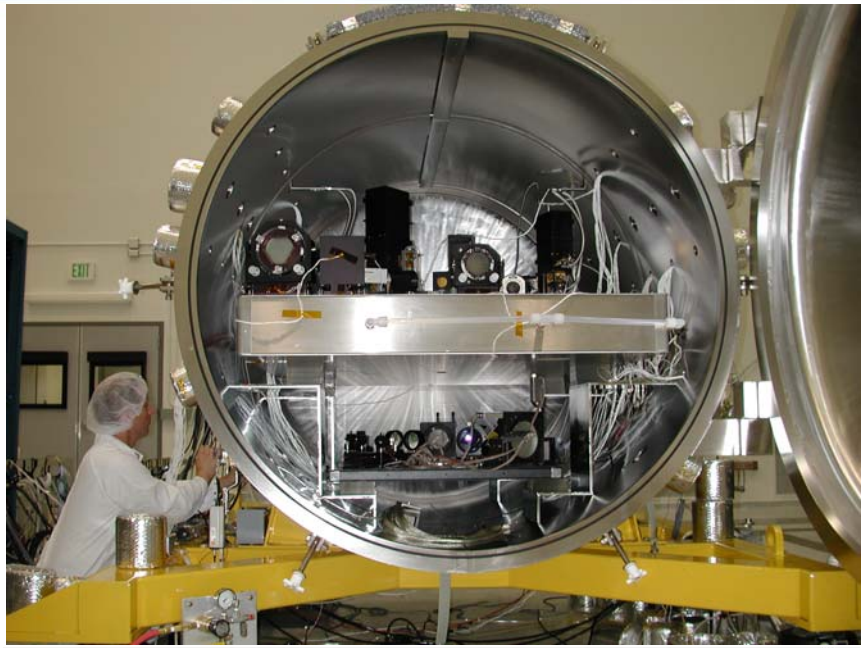
Coronagraph Point Design

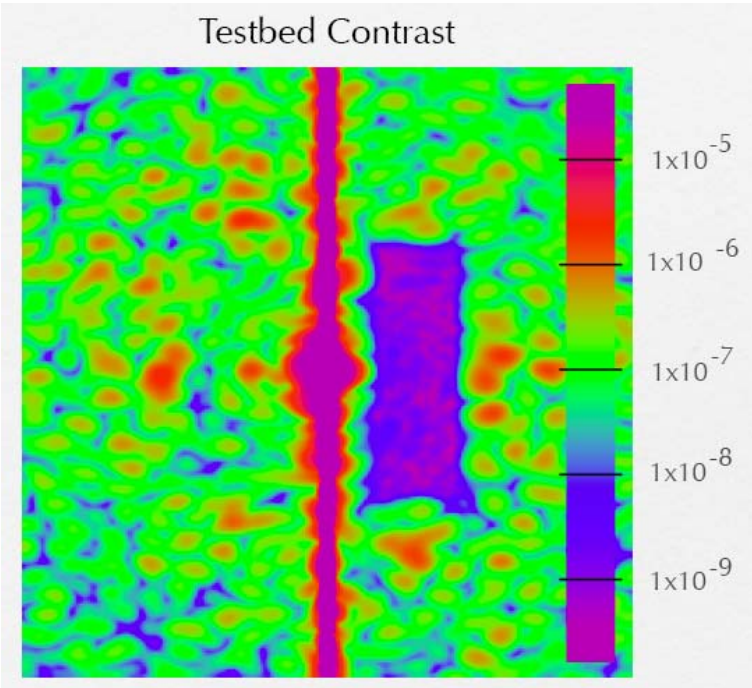


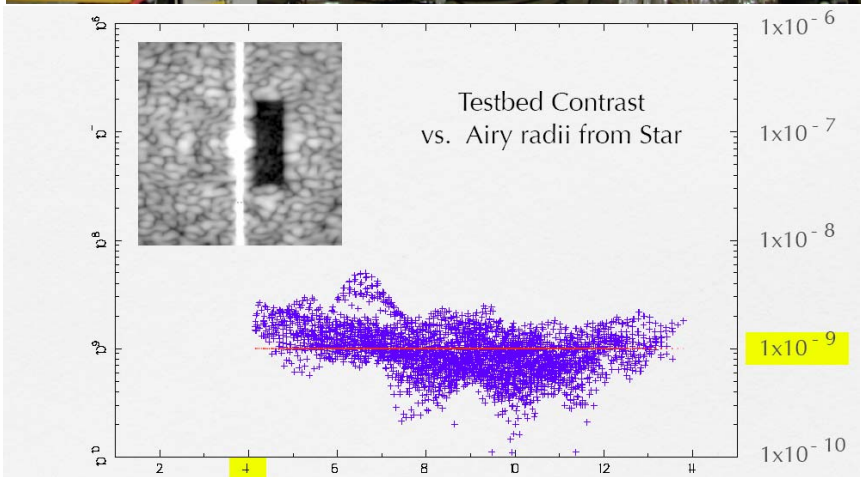
TPF Terrestrial Planet Finder

High Contrast Imaging Testbed

- HCIT:
  - Deformable mirrors
  - Wave Front Sensing and Control
  - Algorithm Development
  - Masks and Stops performance
  - Signal Processing







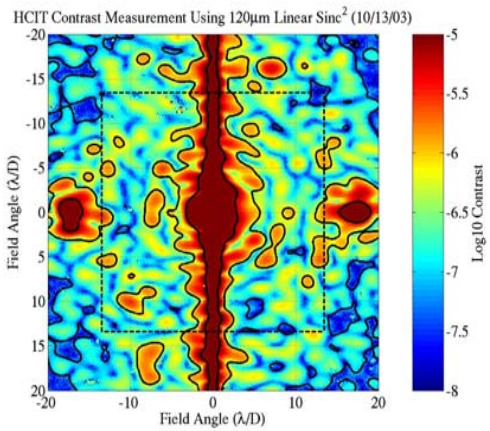
Inner boundary of the target box is 4 Airy radii to the right of the suppressed `star' image. Average intensity of background speckles in the target box is fainter than the `star' by a factor of 9×10^{-10} in 785 nm narrowband (laser) light.

TPF Terrestrial Planet Finder

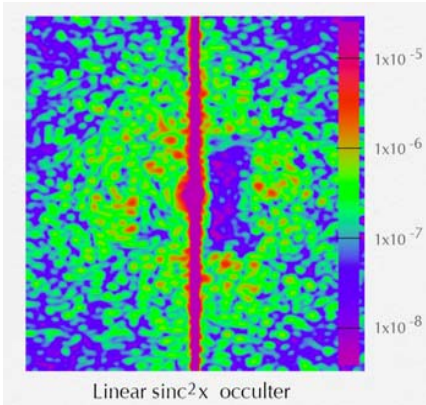
Data from John Trauger 02 Feb 2005

High Contrast Imaging Testbed Data

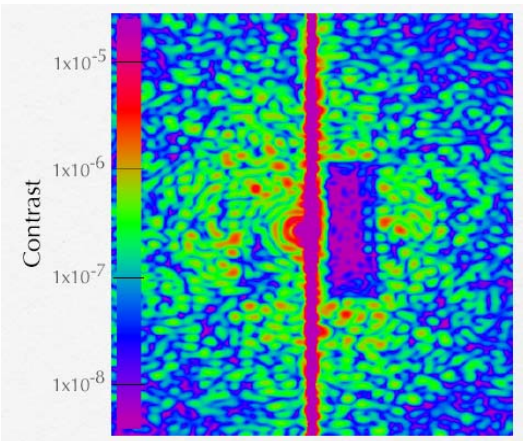
October: 10^{-6}

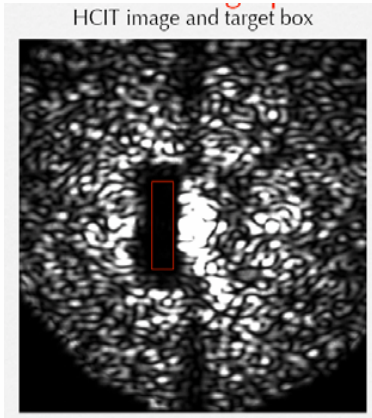


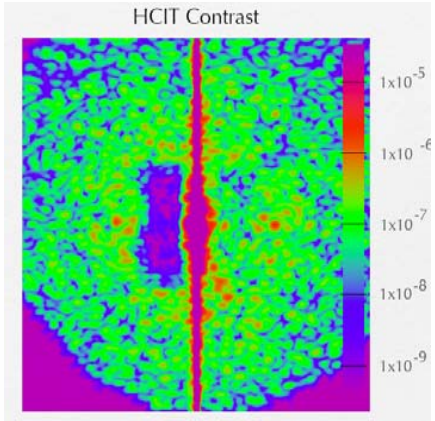
December: $3x10^{-8}$



February: $8x10^{-9}$







HCIT coronagraph image obtained with a linear occulting mask in June 2004. The inner boundary of the target box is 4 Airy radii to the left of the suppressed 'star' image. Average contrast in the target box is 1.5 x 10-9. Wavefront is corrected using speckle nulling entirely at the science focal plane (Burrows algorithm). Measurement is in narrowband light at 785nm wavelength.

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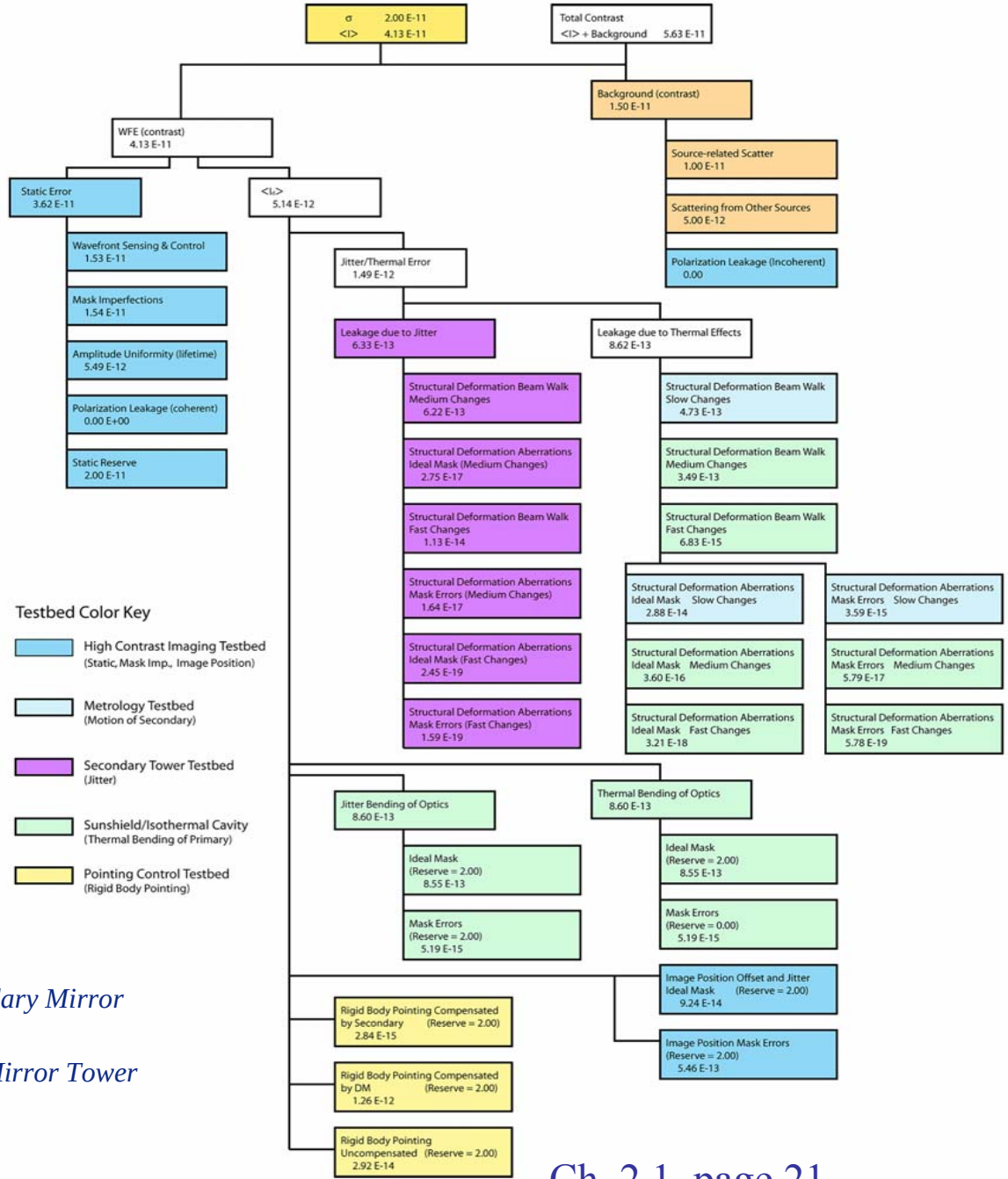
TPF Terrestrial Planet Finder

HCIT measures all instrument terms in the static error budget

HCIT addresses sensitivity of contrast to aberrations, beam walk and pointing

Planned future testbeds address the ability to meet derived requirements: thermal stability, damping, dynamic isolation, etc.



Metrology Testbed ↔ Closed-loop Secondary Mirror Position Control Testbed

Secondary Tower Testbed ↔ Secondary Mirror Tower Partial Structure Testbed

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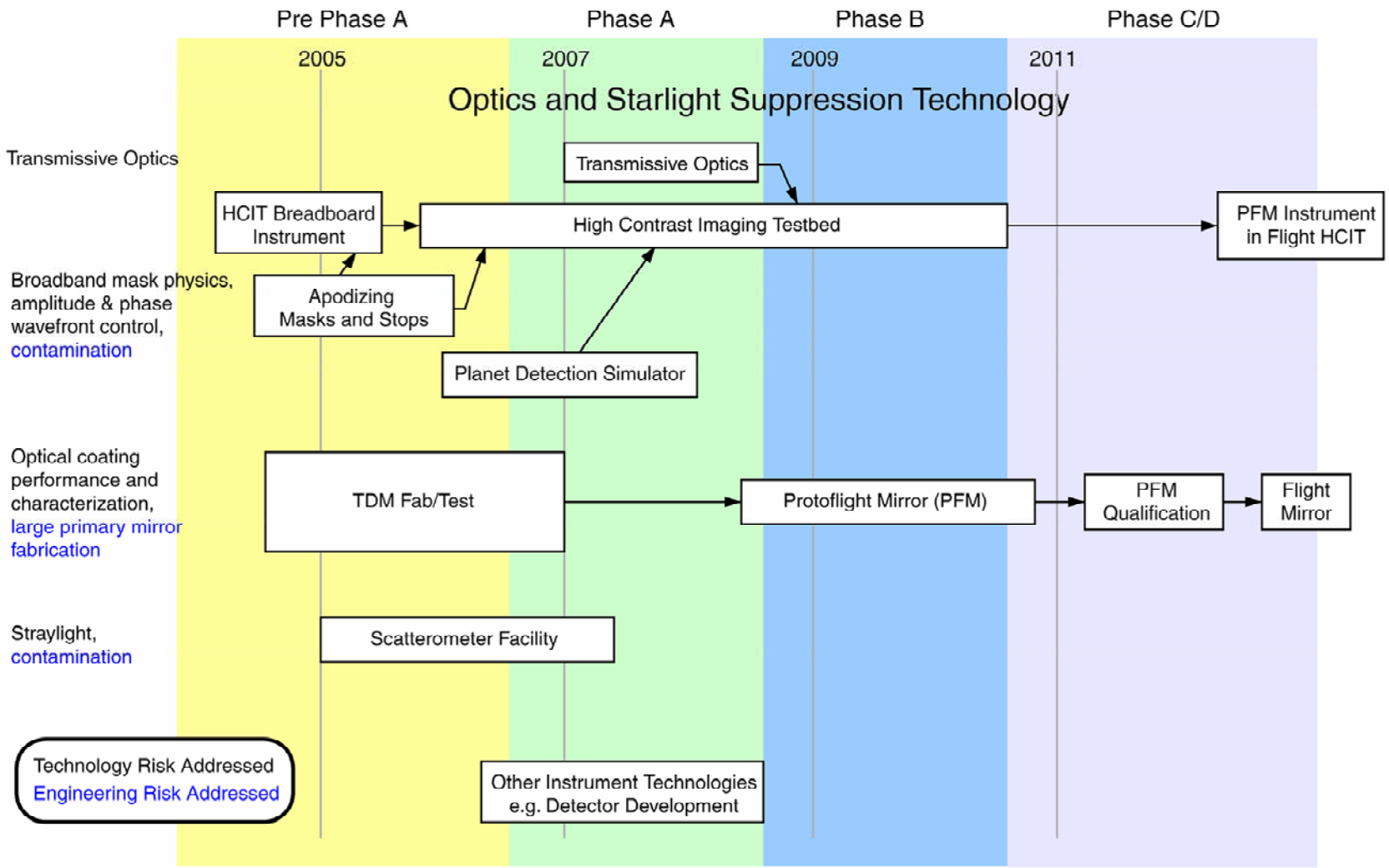
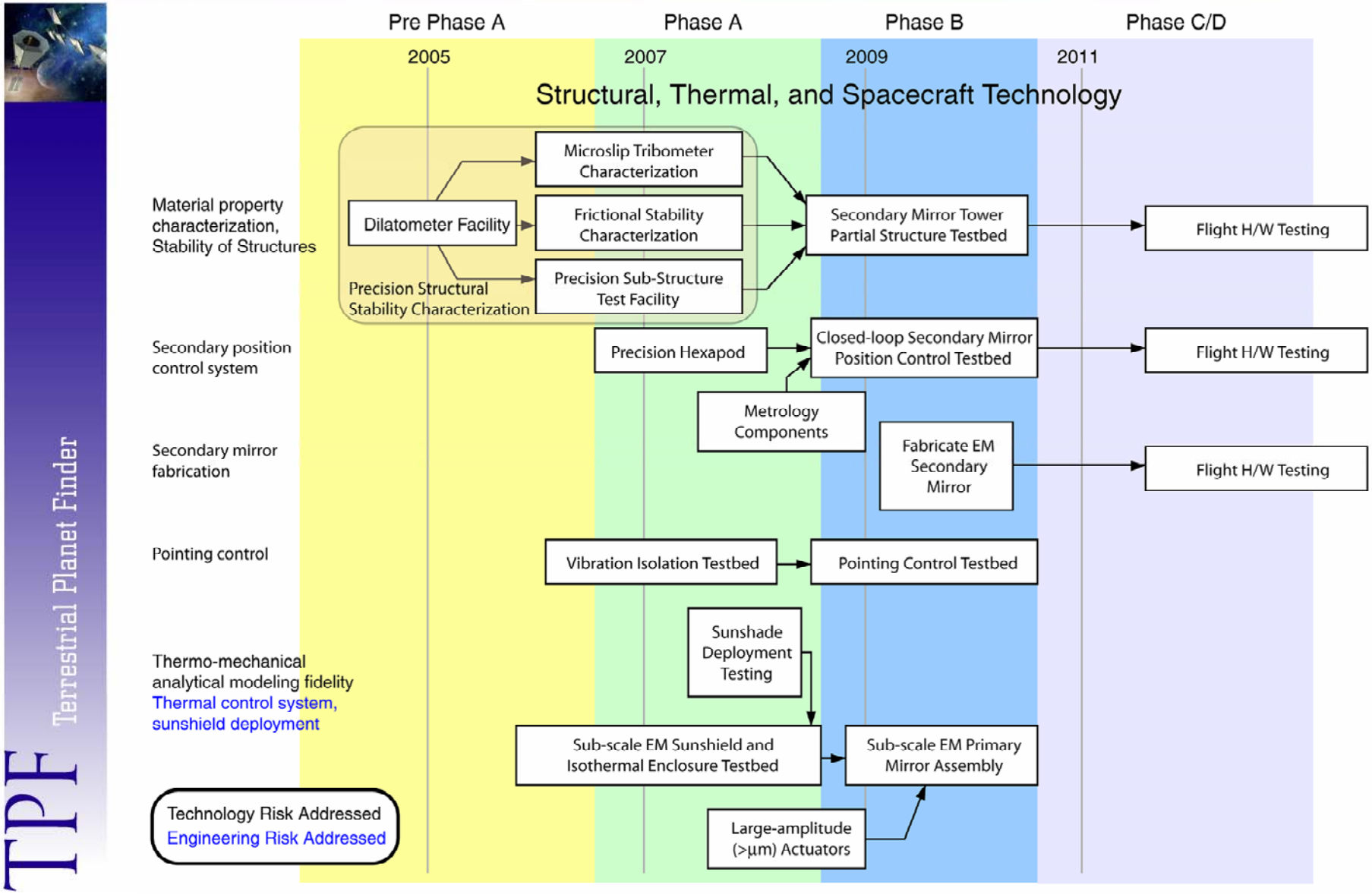
TPF Technology Roadmap



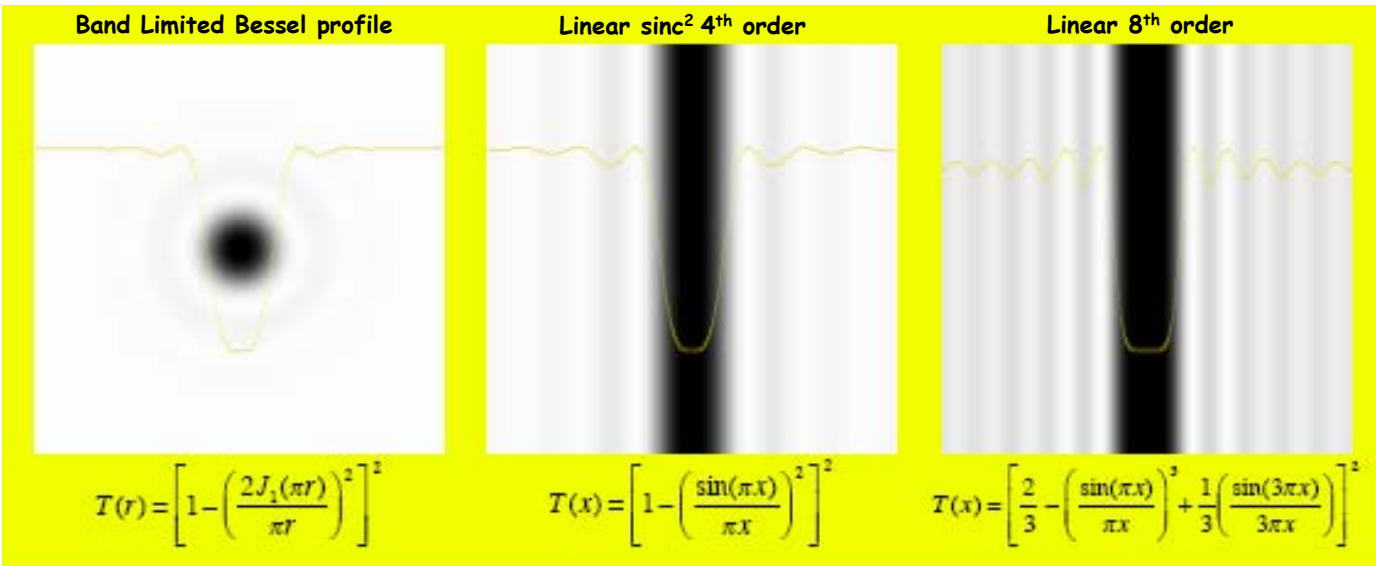
TPF Terrestrial Planet Finder

TPF Technology Roadmap



Masks and Stops Development: HEBS

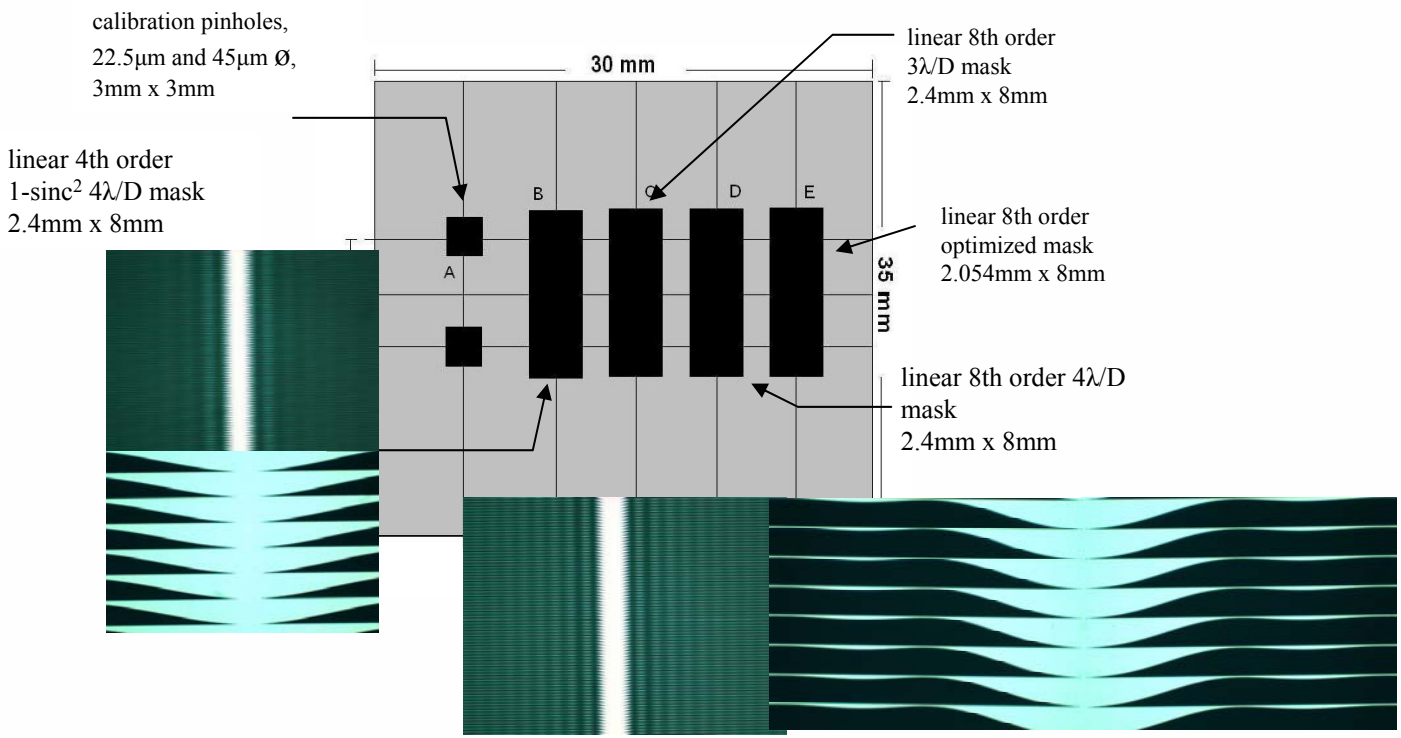
- HEBS glass irradiated with high energy electron beam
- HEBS glass manufactured by Canyon Materials, Inc.
- High dynamic range in optical density (OD from 0 to 8)
- Precision electron beam writing
- Testbed implementation
  - Current HCIT results from linear sinc^2 (4th order)
  - 8th order in fabrication



Transmittance profiles for three candidate occulting spot apodizations. From left to right: a band-limited Bessel profile, a linear sinc^2 (4th-order) profile (Kuchner and Traub 2002), and a linear 8th-order profile (Kuchner, Crepp, and Ge 2004). The linear sinc^2 mask has been fabricated both in HEBS glass and as a binary mask on glass. The 8th-order masks are currently in fabrication at JPL.

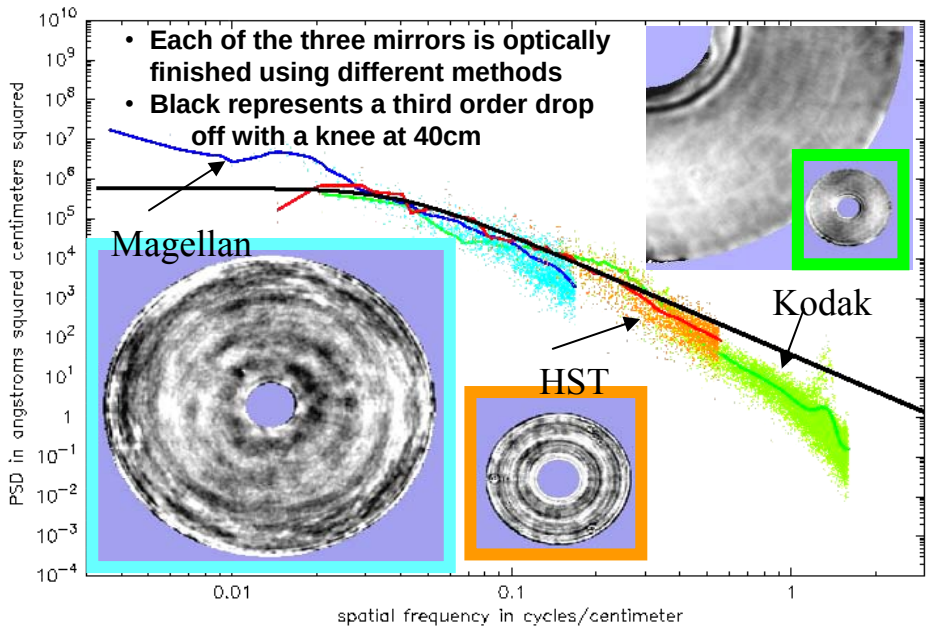
Masks and Stops Development: Binary

- E-beam lithographically patterned aluminum on glass
  - Patterning is done on the same equipment as HEBS masks
- Both continuous and discontinuous versions
- Binary linear 1-sinc^2 and 8th order mask
- Testbed implementation on HCIT planned

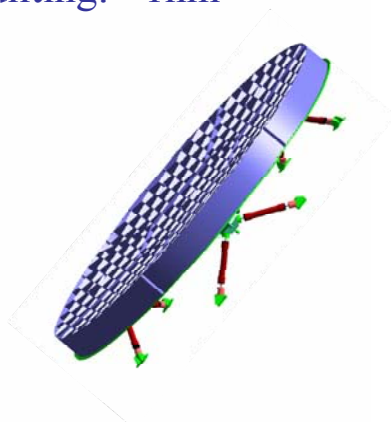


Optical microscope photos of portions of recently completed mask set

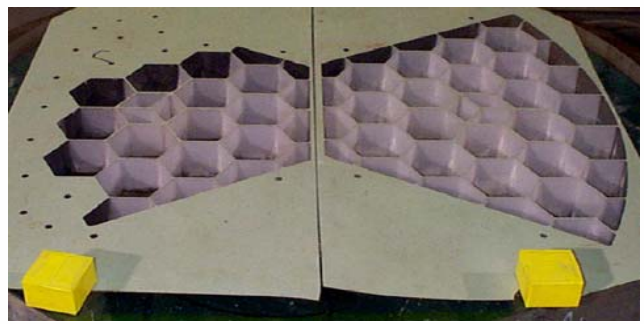
Technology Demonstration Mirror



Corning ULE™
Segmented core
Low temp fused and slumped
Areal density: 45.4 kg/m^2
First free mode: 259 Hz
First mounted mode: 87 Hz
On-orbit PV quilting: <1nm correctable



Parameter	Range	Requirement	Goal
SURFACE ERROR REQUIREMENTS			
Low Spatial Frequency (LSF)	<0.025 cycles/cm	10 nm rms	5nm rms
Mid Spatial Frequency (MSF)	0.025 – 0.5 cycles/cm	5 nm rms	2.5 nm rms
High Spatial Frequency (HSF)	0.5-10 cycles/cm	1.4 nm rms	0.7 nm rms
Micro-roughness	>10 cycles/cm	10 Å rms	5 Å rms
COATING RESIDUAL REFLECTANCE REQUIREMENTS			
Mid Spatial Frequency (MSF)	0.025 – 0.5 cycles/cm	<0.3% rms	²0.1% rms



Deformable Mirrors

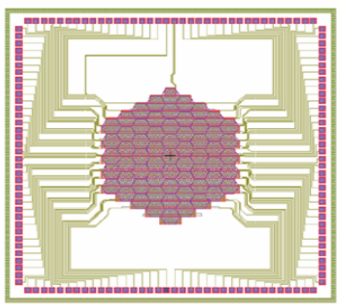
Deformable Mirror Property	State of the Art - MEMS*	State of the Art - Xinetics	TPF-C Flight Baseline
Actuators across aperture	32 actuators/pupil	64 actuators/pupil	96 actuators/pupil
Actuator spacing	3.3 actuator/mm	1 actuator/mm	≥ 1 actuator/mm
Command resolution	~5 □ surface/step	< 0.10 □ surface/step	< 0.05 □ surface/step
Actuator stroke	~20000 □ surface [a]	> 2000 □ surface	> 2000 □ surface
Actuator position stability	TBD	< 0.20 □ surface/hour (includes effects of 10 mK thermal stability)	< 0.02 □ surface/hour
Actuator thermal stability	TBD	~ 3.5 % of stroke / K	TBD
Mirror surface quality at uncontrollable spatial scales	~10 nm surface [¤]	< 10 □ surface	TBD

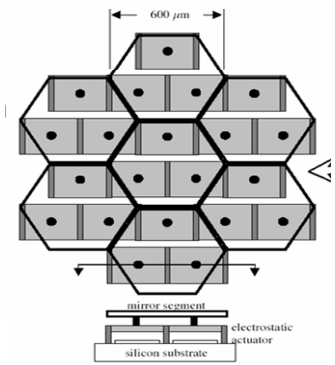
* Based on Boston MicroMachines Devices

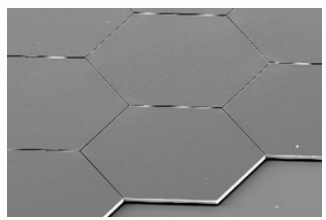
C ommand resolution is currently limited by the precision of the high voltage drivers with an average step size of ~10 nm/V; with custom 16-bit electronics, an average 0.3 □/step is expected. Current devices on order are expected to achieve up to 12-13 bit resolution or 4.9-2.4 □/step.

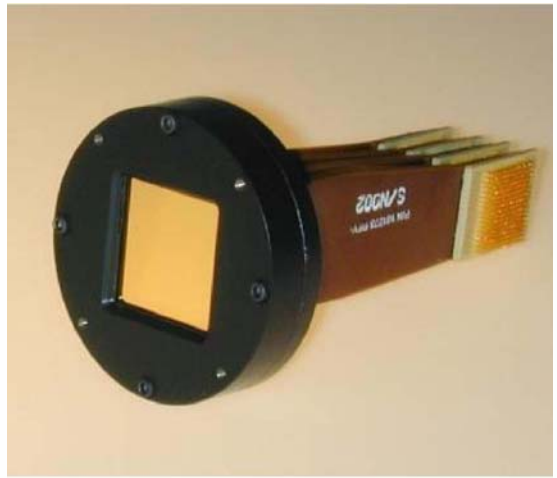
ą Nominal actuator stroke is ~20,000 □ (2 μm), however usable stroke over full aperture is limited by unpowered, surface curvature to somewhat less than this.

¤ Small area, periodic deviations at actuator frequencies (2x outer working angle frequency) in unpolished devices. Devices on order are being polished to reduce this level.





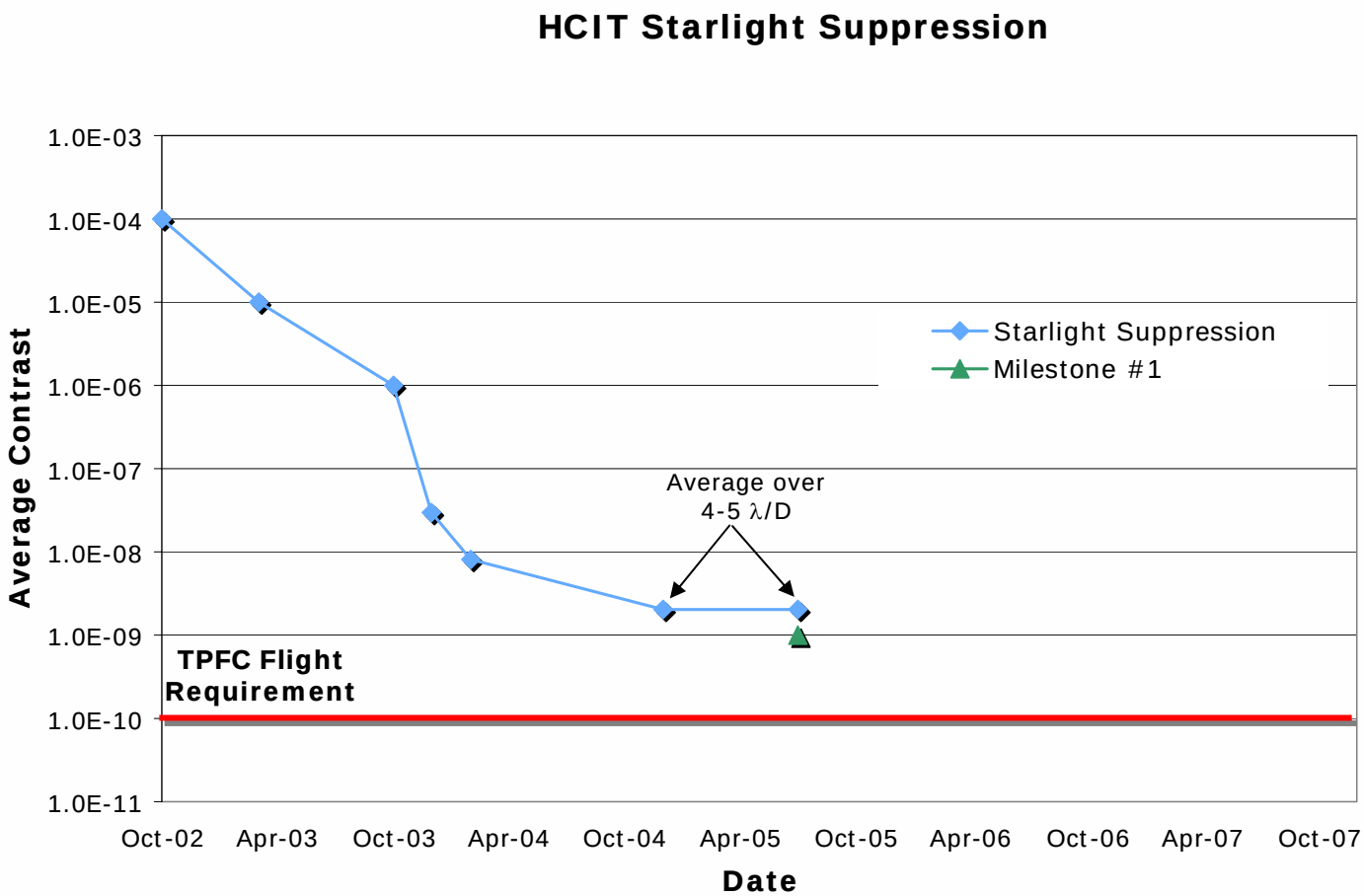




Single-module DM (32x32 mm, 1024 actuators)

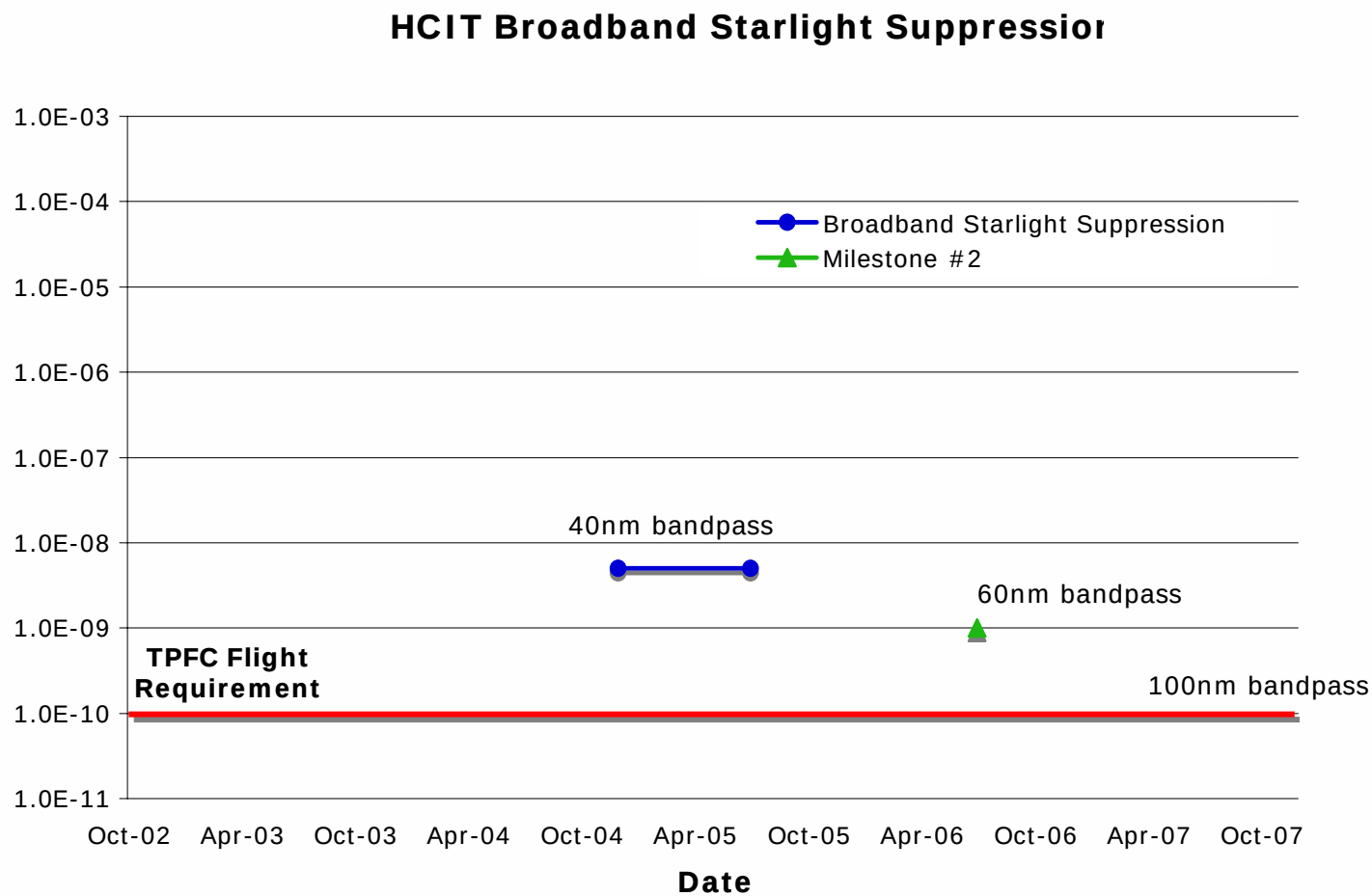
Four-module DM (64x64 mm, 4096 actuators)

Starlight Suppression Metrics



These measurements refer to an average contrast over a half-dark hole from 4-10 λ/D, unless otherwise noted. Contrast is defined as the ratio of the residual light level at a point in the focal plane to the light that would appear if the source image was centered at that point.

Starlight Suppression Metrics

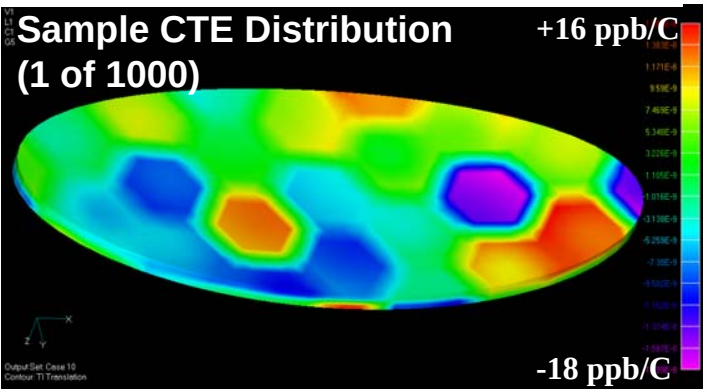


These measurements refer to an average contrast over a half-dark hole from 4 - 10 λ/D. Contrast is defined as the ratio of the residual light level at a point in the focal plane to the light that would appear if the source image was centered at that point.

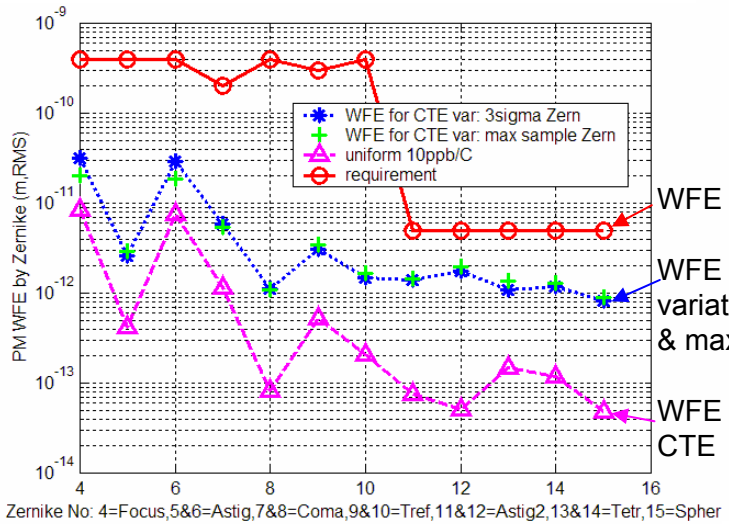
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

TPF-C System Studies
Flight Baseline 1 Concept

Results of Primary Mirror Performance Analysis

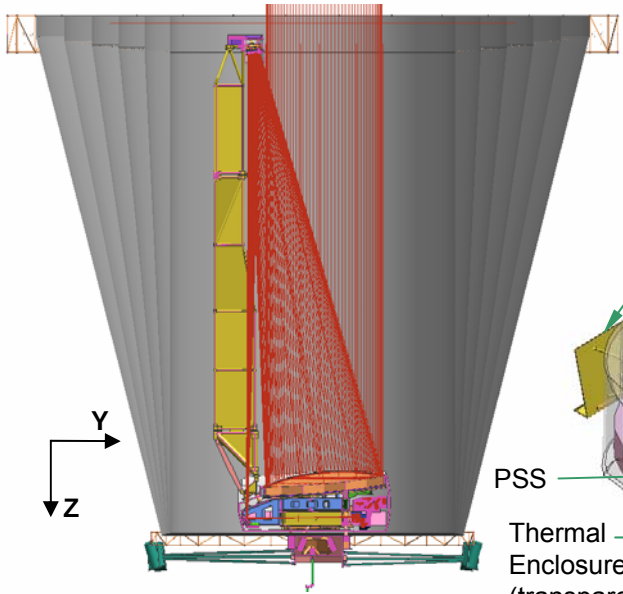


Worst case dither WFE including CTE Variation with Temperature Dependence (2ppb/C/C)

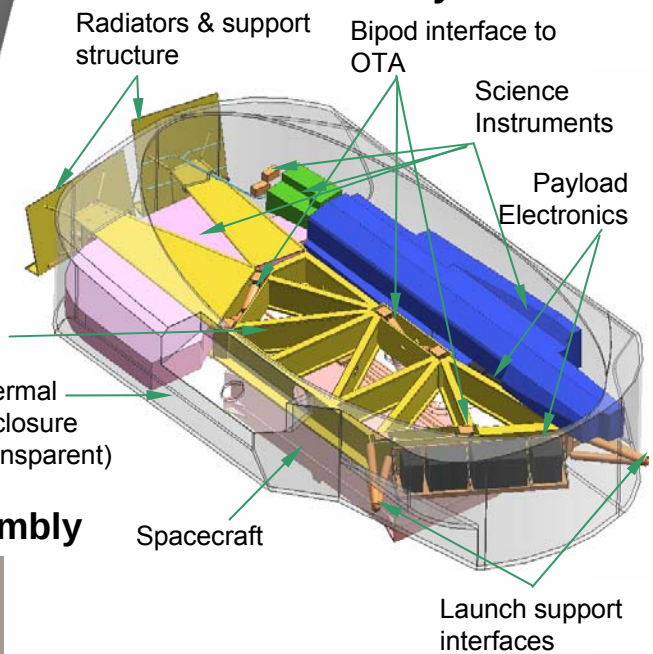


Zernike Component Number (4= Power/Focus, etc)

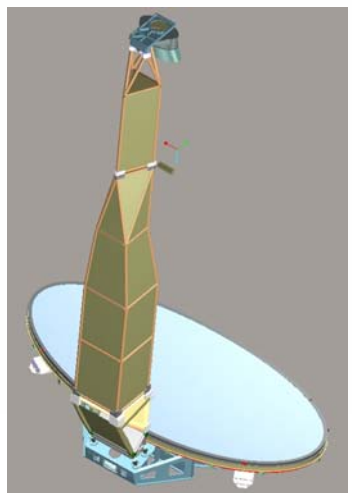
TPF-C Observatory
(Solar Panels and Sail not shown)



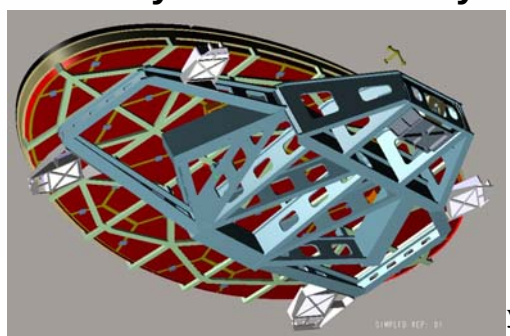
TPF-C Instrument Assembly



Optical Telescope Assembly

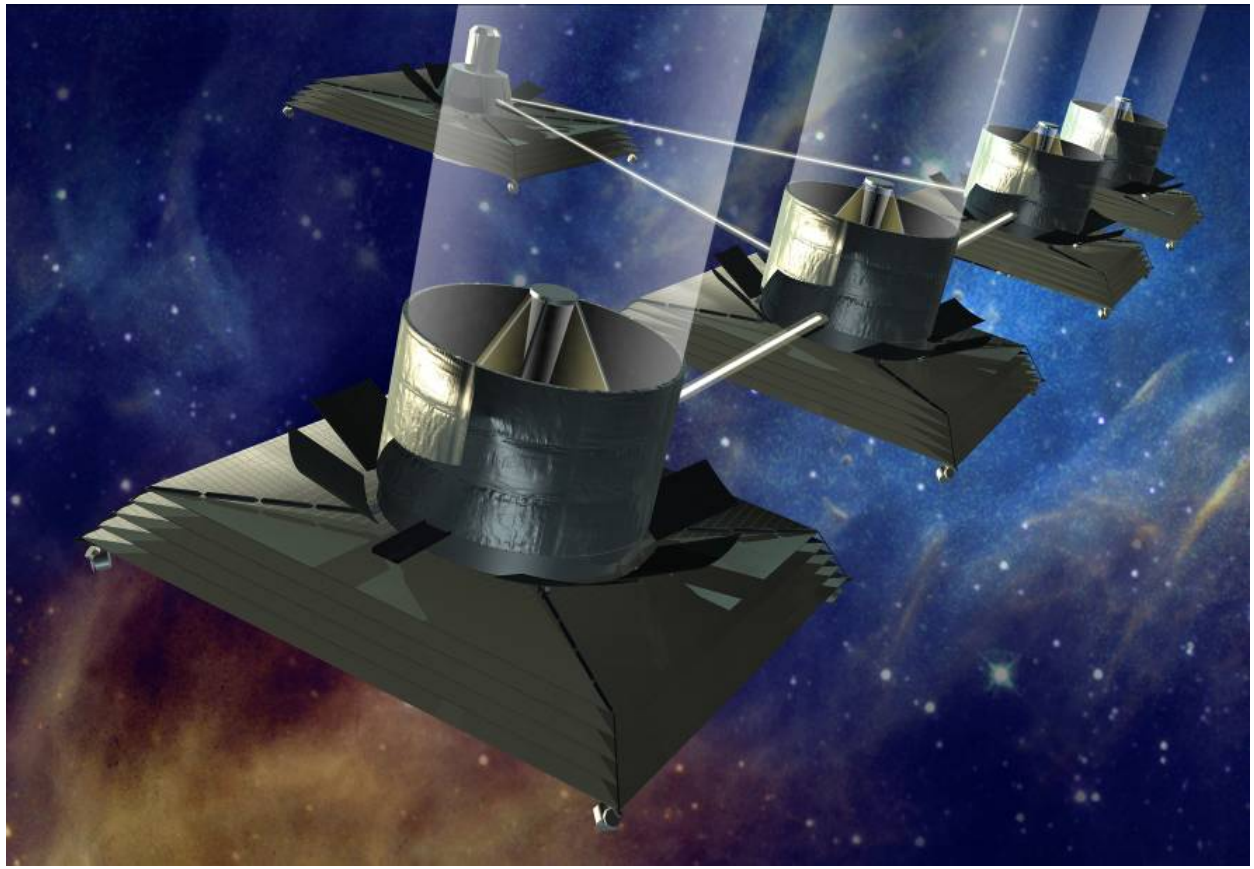


Primary Mirror Assembly

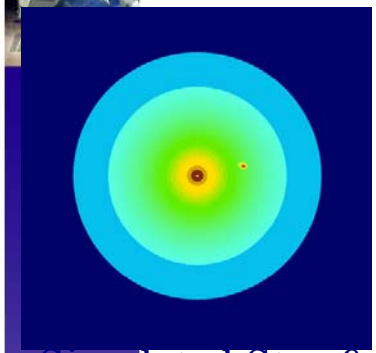


TPF Terrestrial Planet Finder

TPF Interferometer

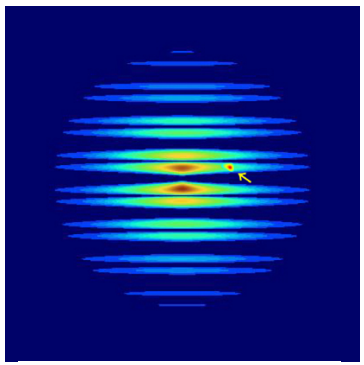


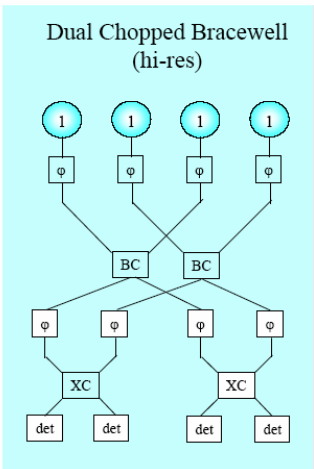
How a nulling interferometer works



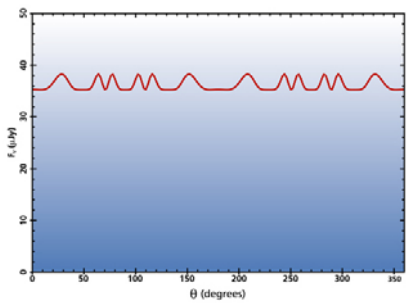
Simulated Star & planet field

Fringe pattern is designed to block out the star light

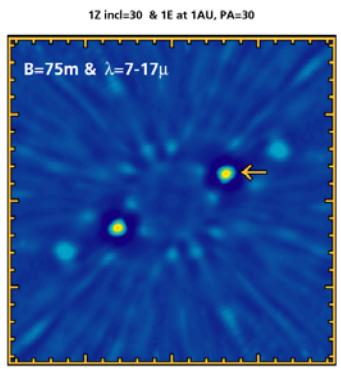




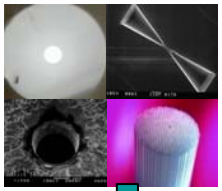
The fringe pattern is rotated to bring the planet in and out of transmission



The data are then processed to produce a reconstruction of the system

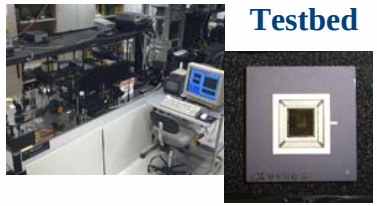


Interferometer Technology

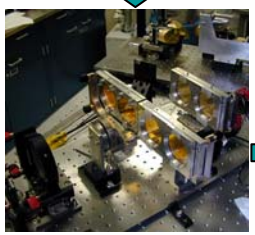


Mid-Infrared Spatial Filter Technology

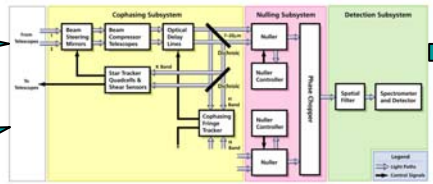
Adaptive Nulling Testbed



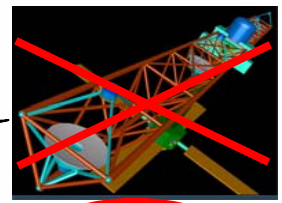
Achromatic Nulling Testbed

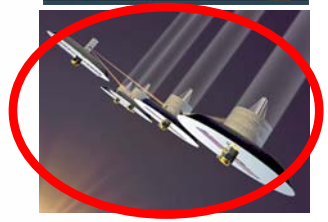


Planet Detection Testbed

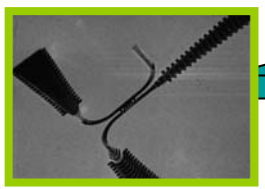


Interferometer Point Designs

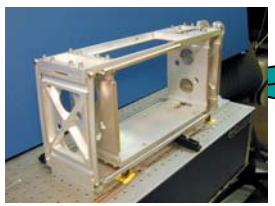


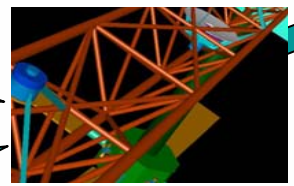


Advanced Nulling Technology

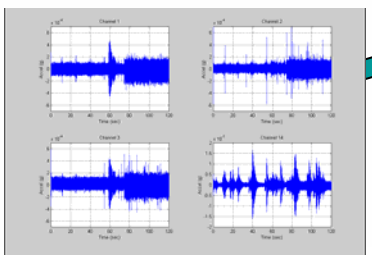


Cryogenic Delay Line





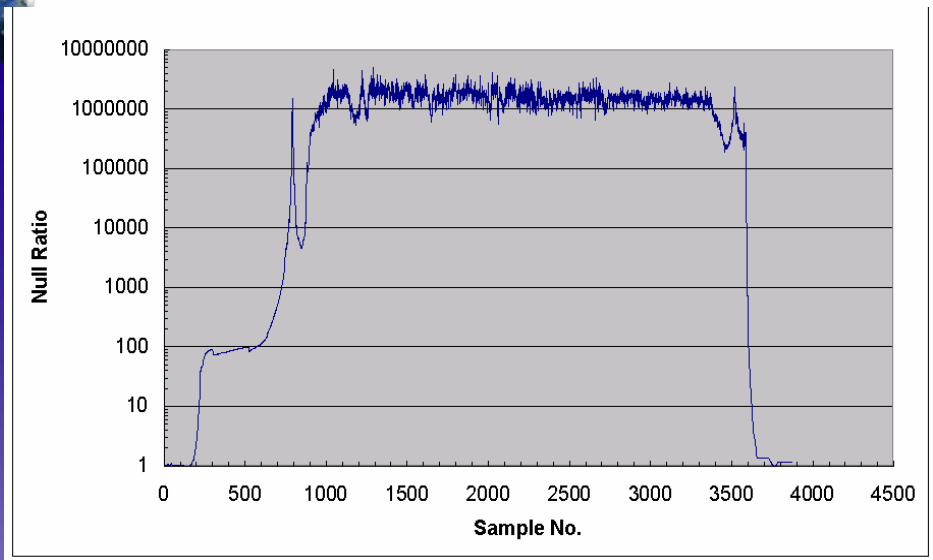
Structurally Connected Interferometer Testbed



Cryogenic Structures and Modeling Technology

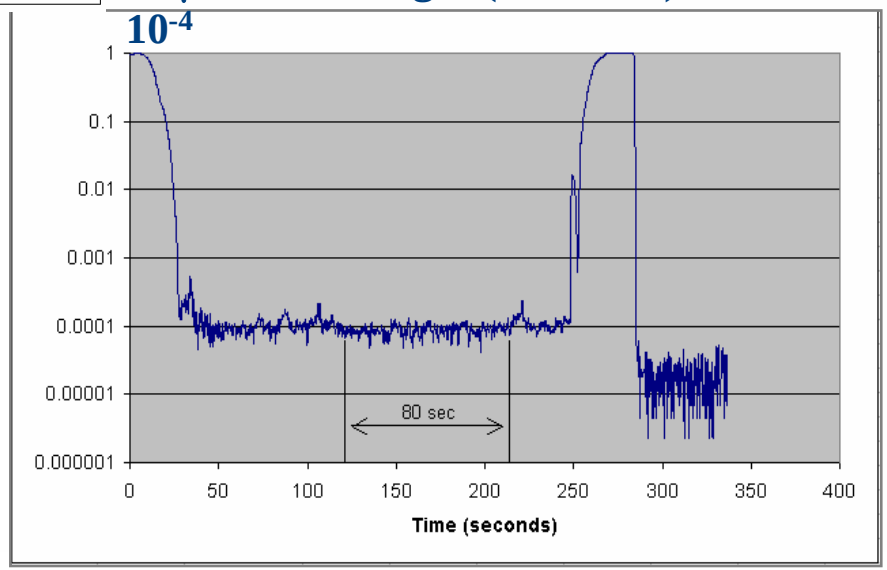
TPF Terrestrial Planet Finder

Achromatic Nulling Testbed Data



10 μm Laser Null: better than 10^{-6}

10 μm White Light (30% BW) Null: 10^{-4}



Planet Detection Testbed (PDT)

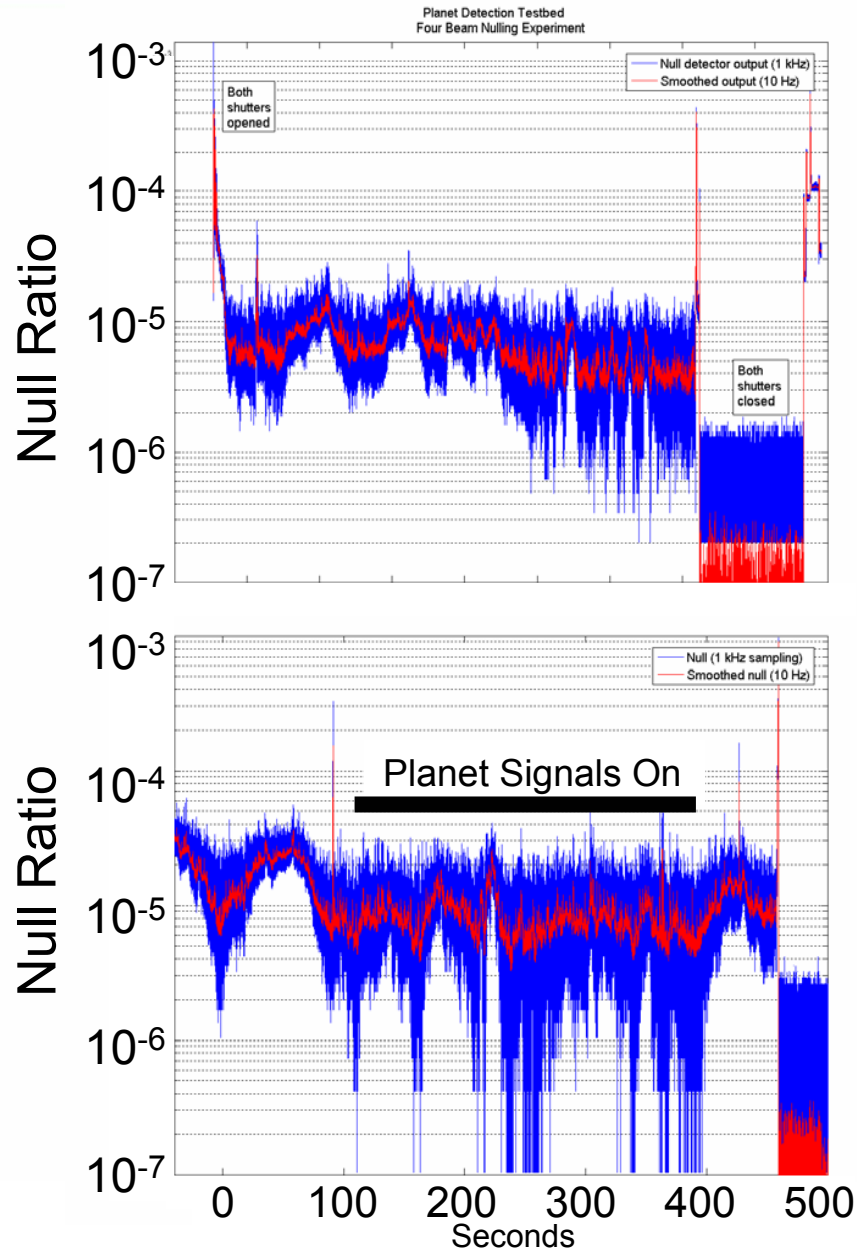
TPF Terrestrial Planet Finder

Four beam nulling @ 10 μm

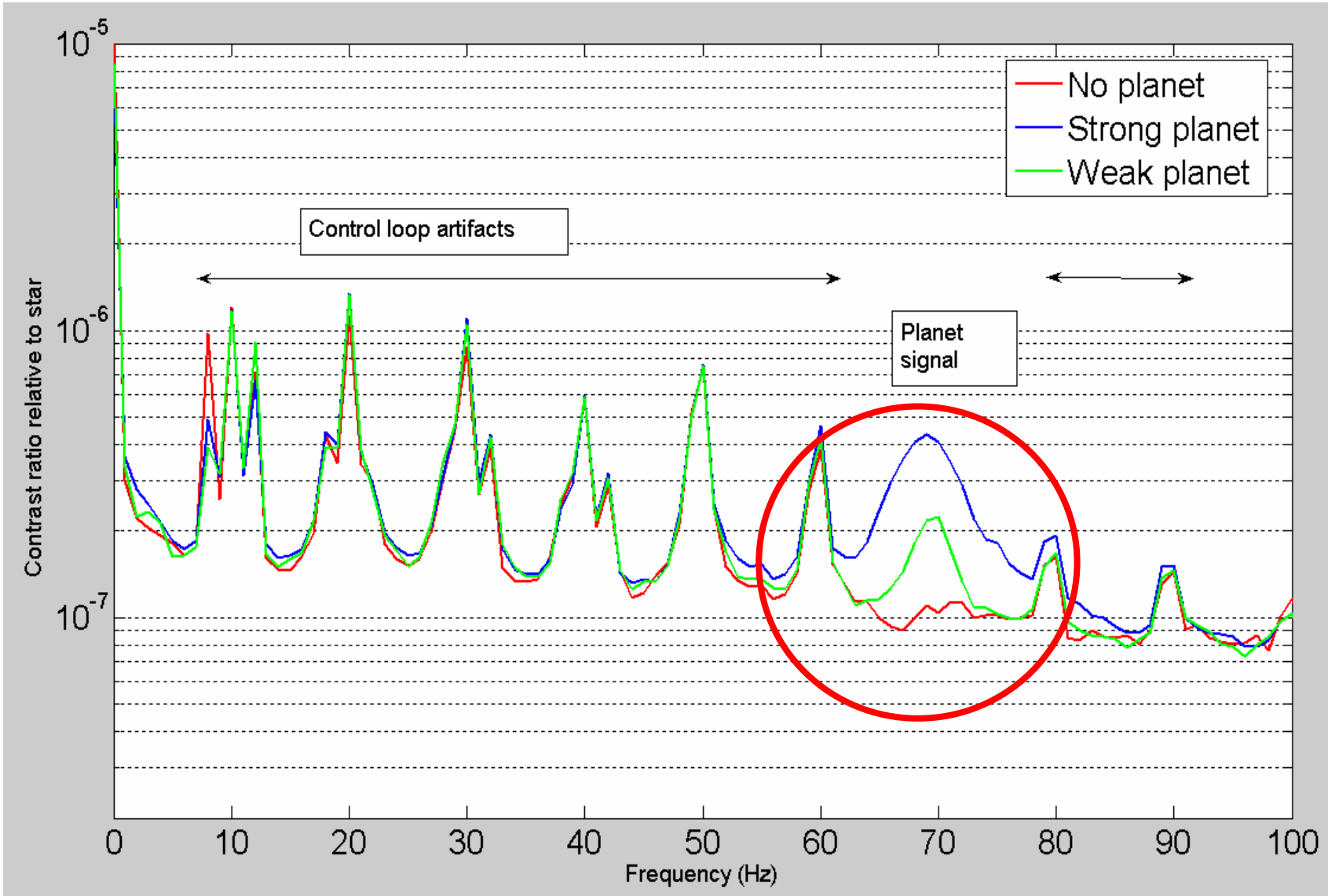
- > 100,000:1 mean null depth
- > 10 minutes
- Four control loops dithering the nulls
- Noise floor is detector limited

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



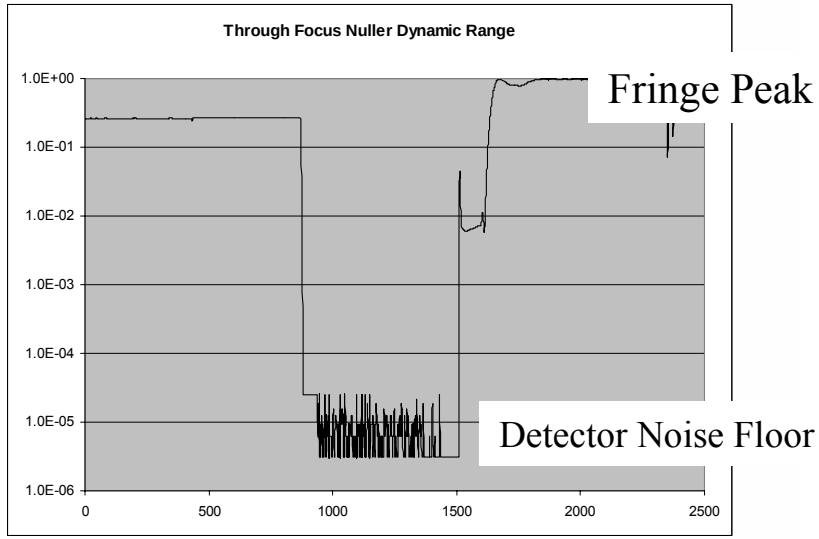
PDT Spectrum Showing Planet Detection at 70 Hz

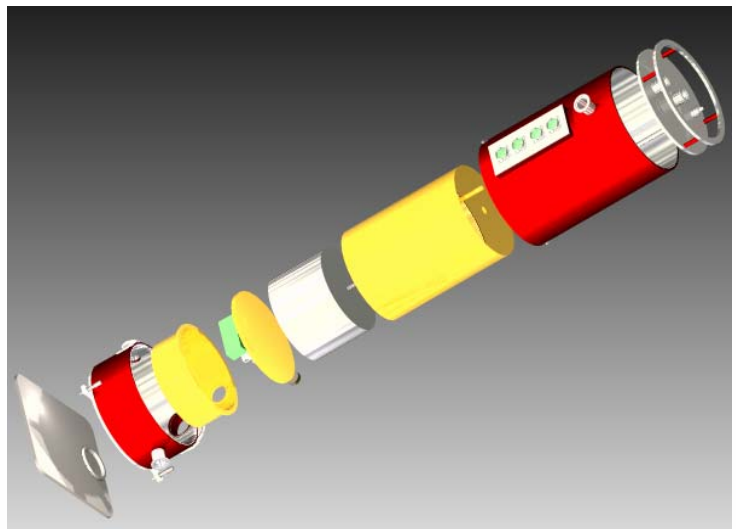


TPF Terrestrial Planet Finder

TPF-I: Broadband Nulling

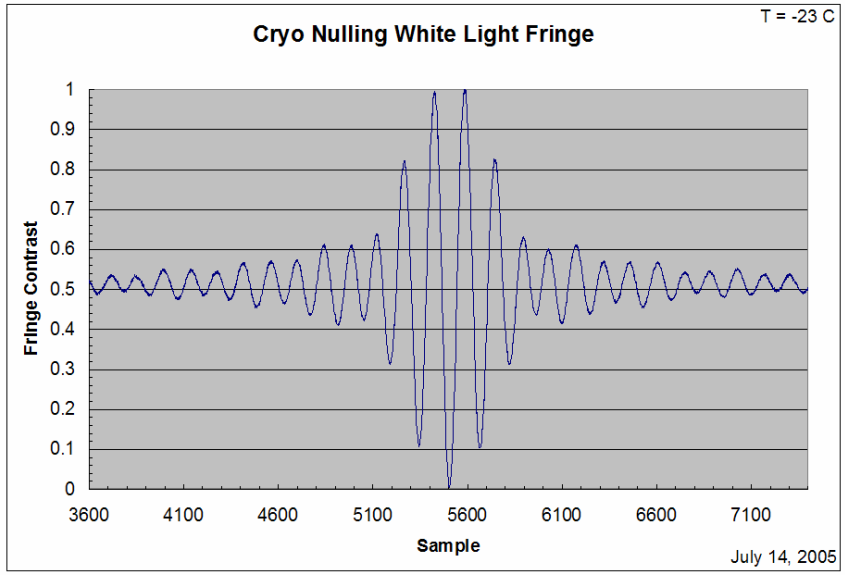
- Previous experimental set-up did not have dynamic range necessary to demonstrate broadband nulling at ratios >10,000:1
  - Limited by dim source
  - Limited by detector noise
  - *Possibly* limited by phase delay nuller architecture
- Arc source has been integrated
  - Working at full power on the arc source, and at the full bandpass of 30%, the dynamic range (fringe peak to detector noise floor) is currently about 50K:1
- Dewar received
- Still coming
  - New detector (factor of 10)
  - AR coated spatial filters (factor of 2.5)
- The through-focus nuller is now in its final build and alignment

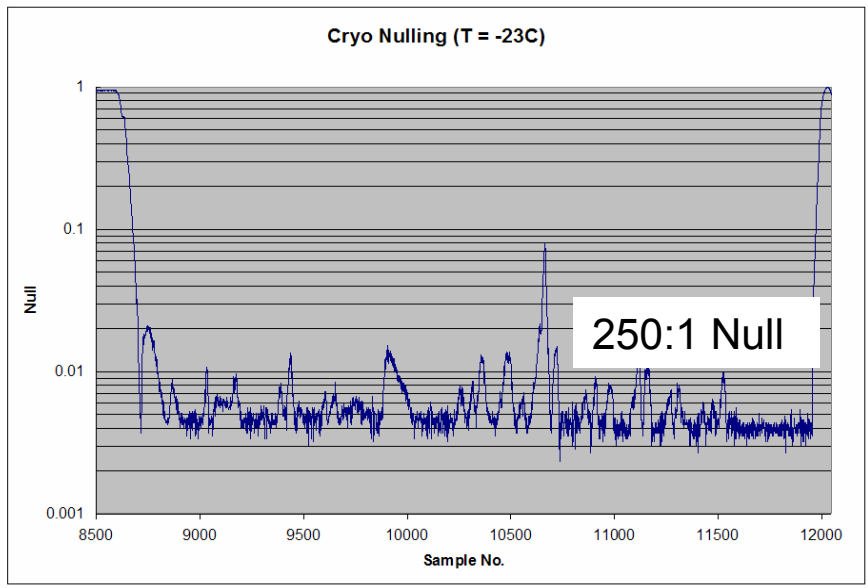




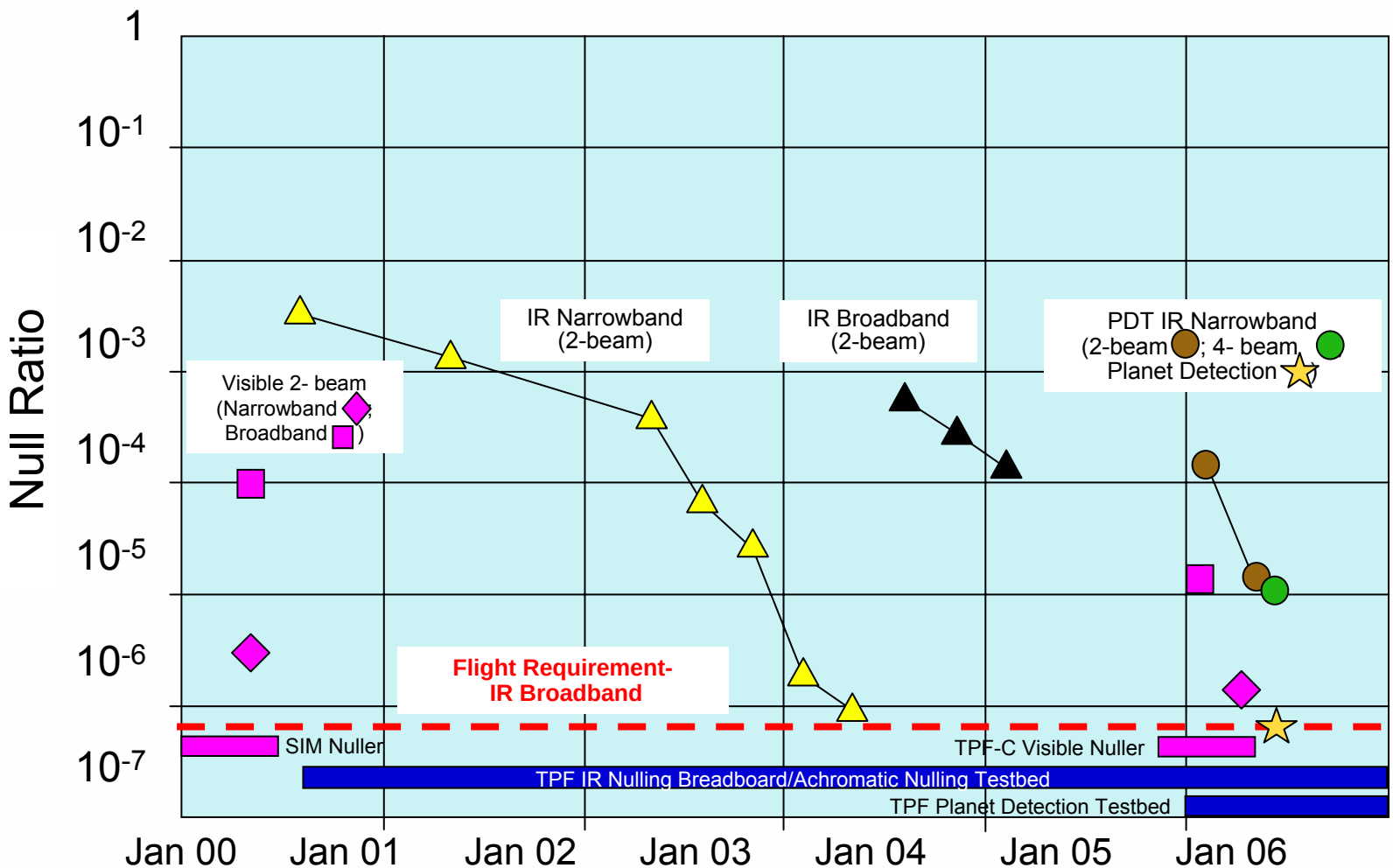
TPF-I: Cryo-Nulling

- Continuing to identify and resolve problems
  - Beamsplitter mount problem resolved
  - PZT gimbal mount problem resolved
  - Identified breadboard flexing problem
    - Probably due to mounting screws
  - Linear translation stage actuators still seizing at ≈ -70C°
    - Eliminated mounts at the cause
    - Consulting with cryo-mechanisms experts
- Operated breadboard at -23C°
  - Obtained good white light fringe
  - Obtained modest null performance





TPF-I Nulling Metrics

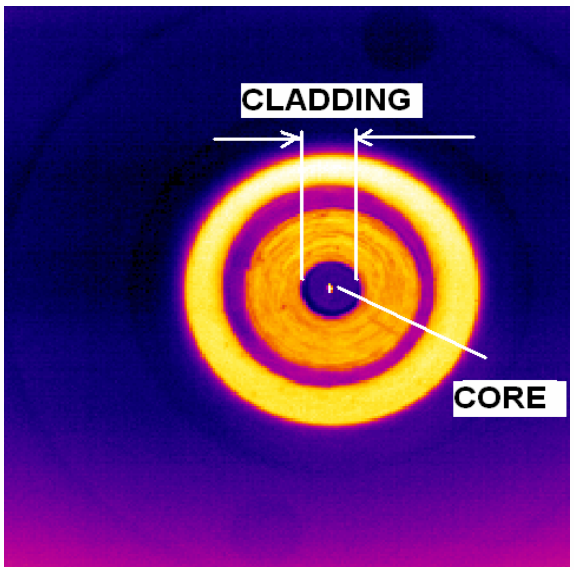


TPF Terrestrial Planet Finder

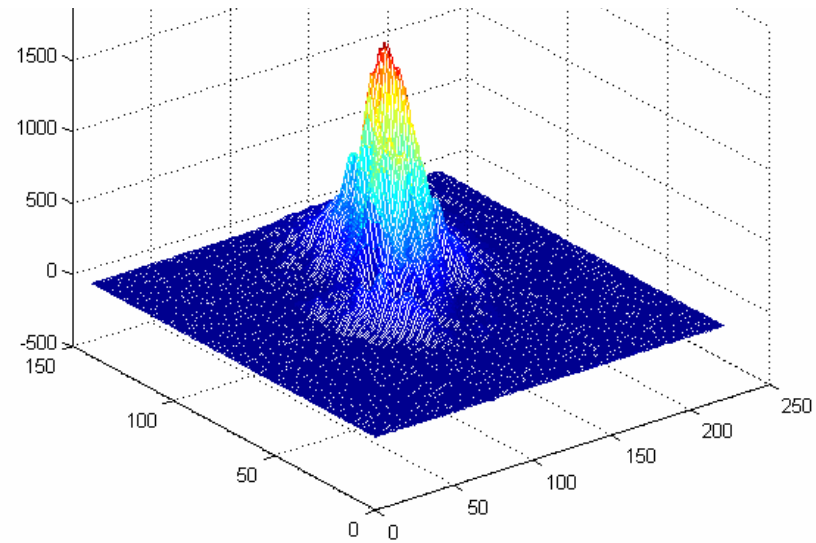
TPF-I: Spatial Filters

- Received last delivery of fibers from NRL and additional deliver of fibers from TAU
- Verified NRL fibers are single mode using testbed that now includes capability to inject asymmetric inputs
- Preliminary evaluation of new TAU fibers indicate probable single mode performance
- NRL fibers are suitable for use from ≈6 to 11μm; TAU fibers are suitable for use from ≈ 6 to ≥20μm

New TAU Fiber with Improved Cladding



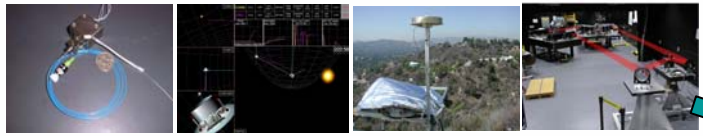
Far field pattern from new TAU Fiber



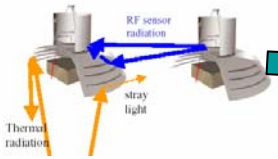
Formation Flying Technology

TPF Terrestrial Planet Finder

Inherited Formation Flying Technologies

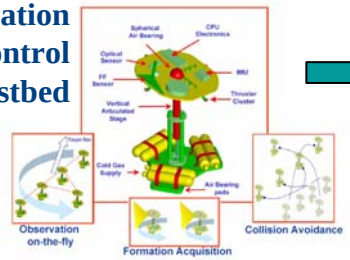


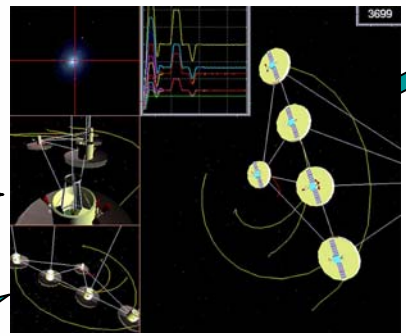
Thermal Shield Technology



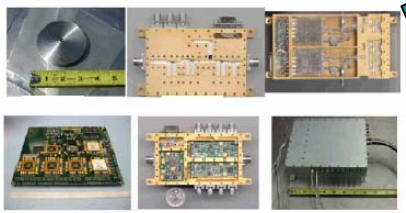
SPHERES Flight Experiments

Formation Control Testbed

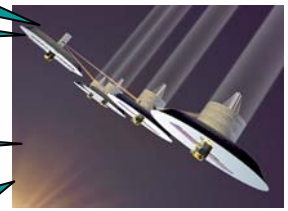




Formation Algorithms and Simulation Testbed



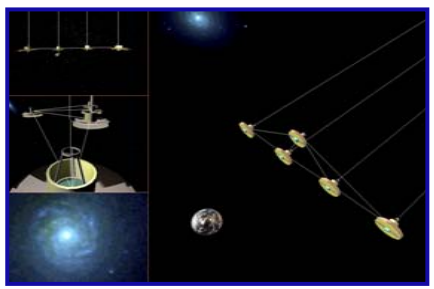
Formation Sensor Technology



Interferometer Point Designs

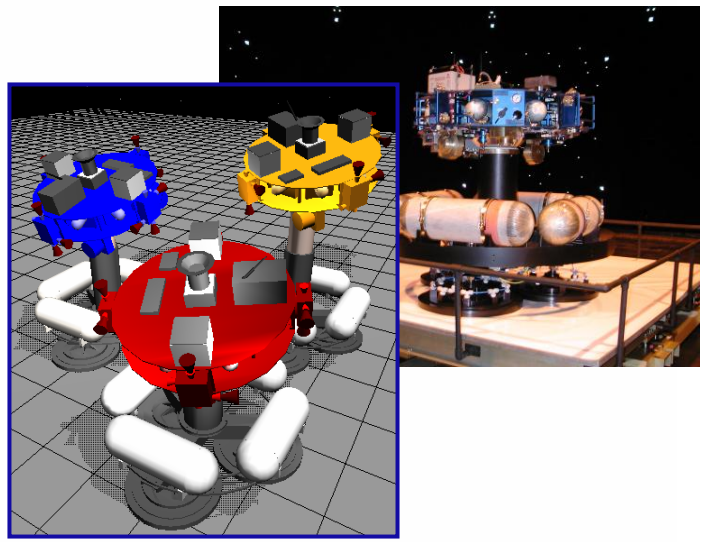
Formation Algorithm & Simulation Testbed: Concept

- FAST demonstrates the end-to-end operation of multiple spacecraft formation flying in a distributed real-time simulation environment.
- Features
  - Scalable real-time distributed simulation environment.
  - Flight-like algorithms on flight-like operating system / CPUs.
  - Autonomous formation maneuvers and target acquisition.
- Scope
  - Demonstrate five spacecraft TPF-like design with TPF FF requirements.
  - Develop robot algorithms and software for Formation Control Testbed.



TPF simulation

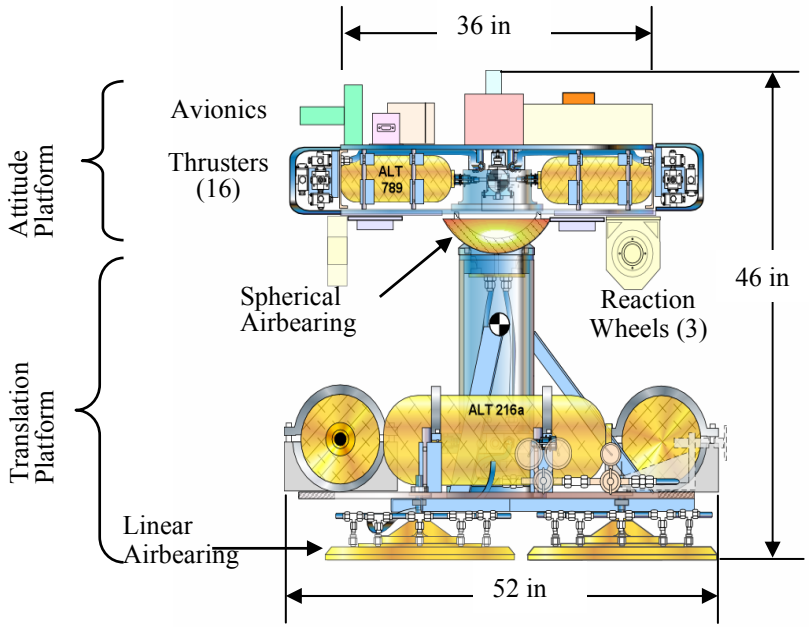
in distributed real-time environment

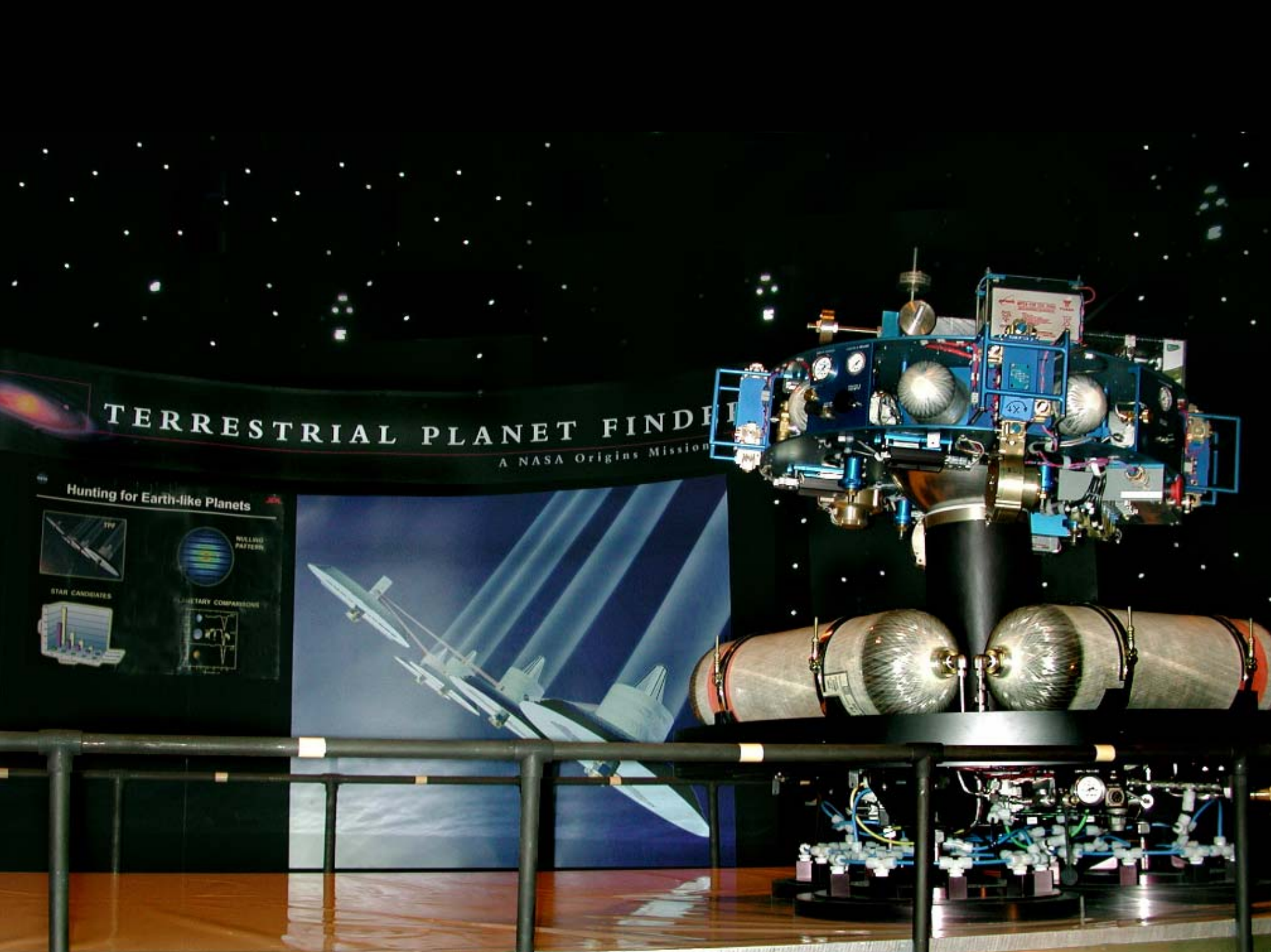


validated against FCT

Formation Control Testbed: Status

- **First robot is operational:**
  - Two floor panels installed
  - Full avionics tested and working:
    - thrusters, reaction wheels
    - celestial sensor, gyros
  - Closed loop attitude control functional.
  - Evaluating truth sensor
  - Calibration of sensors nearly complete.

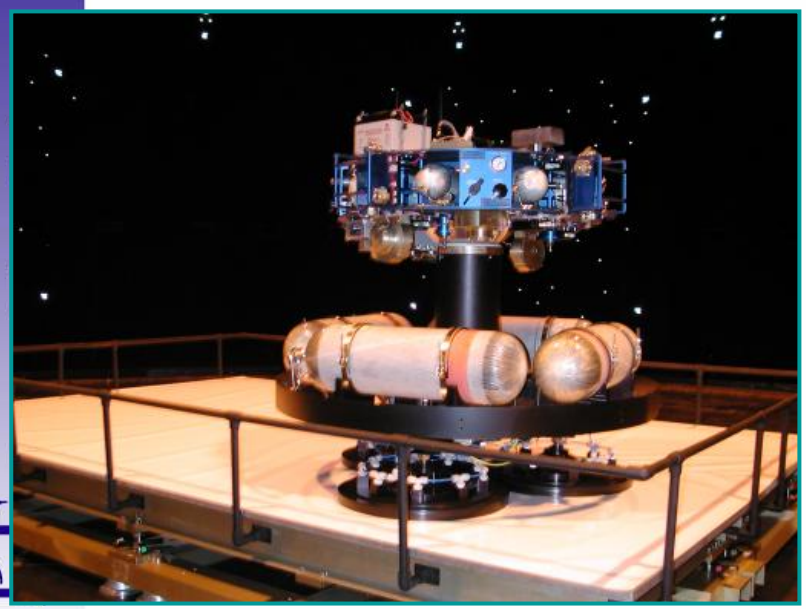



TERRESTRIAL PLANET FINDE
A NASA Origins Mission
Hunting for Earth-like Planets
TPF
STAR CANDIDATES

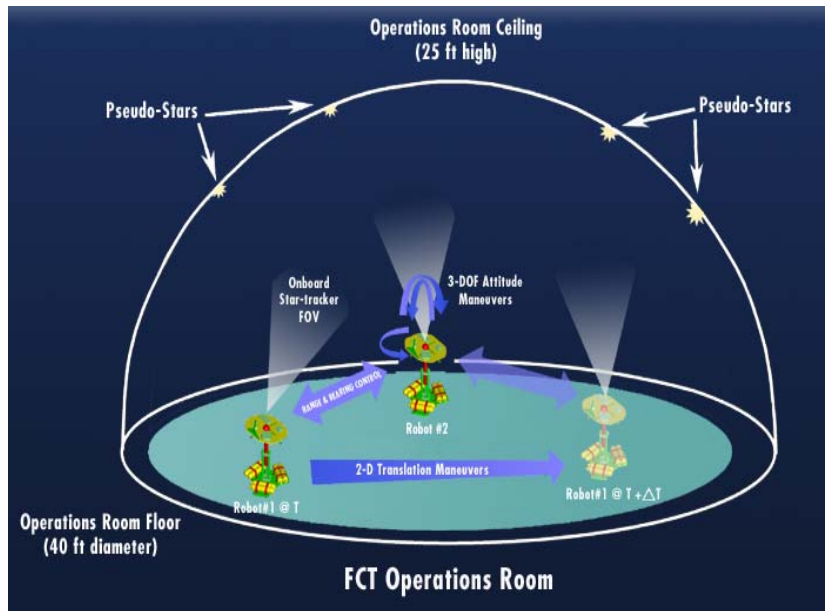
Formation Control Testbed: Concept

- FCT is a hardware testbed to validate formation control architecture and algorithms:
  - Multiple 6-DOF robots using air bearings and vertical articulated arm
  - Flight like avionics: thrusters, reaction wheels, celestial sensor, gyros
  - Share common computational architecture, algorithms and software with FAST

Robot

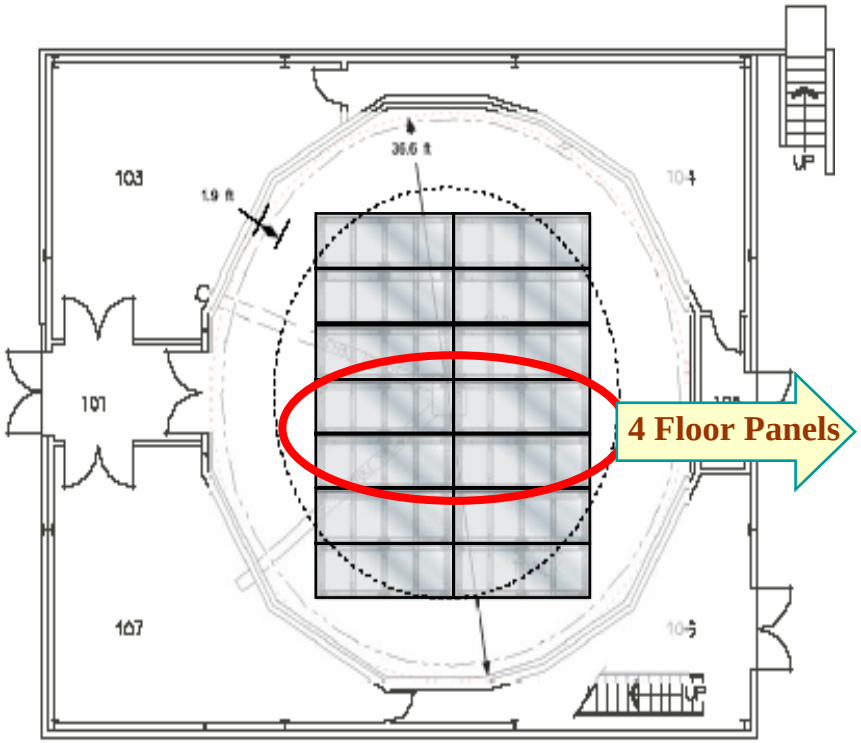


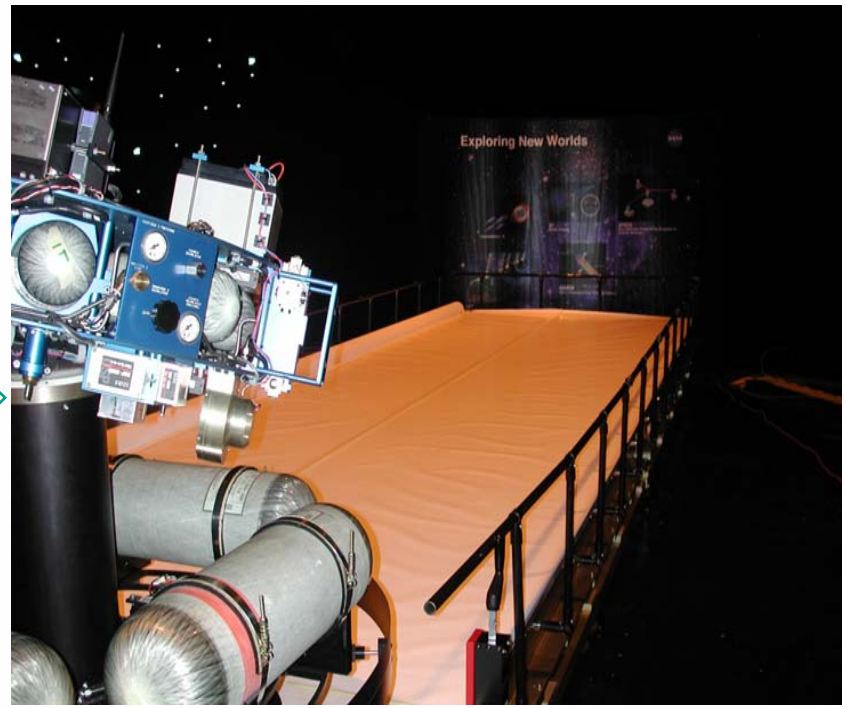
Operations Concept



TPF-I: Formation Control Testbed

- Installed 2 Additional FCT Floor Panels
  - 4 more are due for installation this week
  - All 14 will be in place by November
- Implemented full translation control on Robot #1

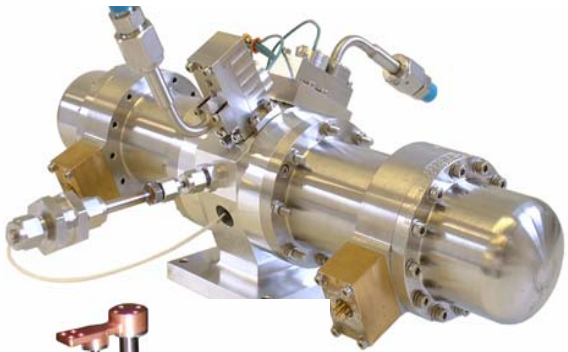


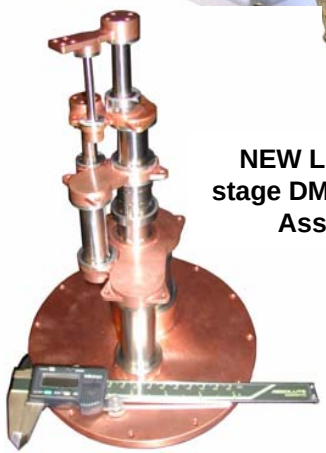


Advanced Cryocooler Technology Development Program

Ball BB Stirling Displacer Parts

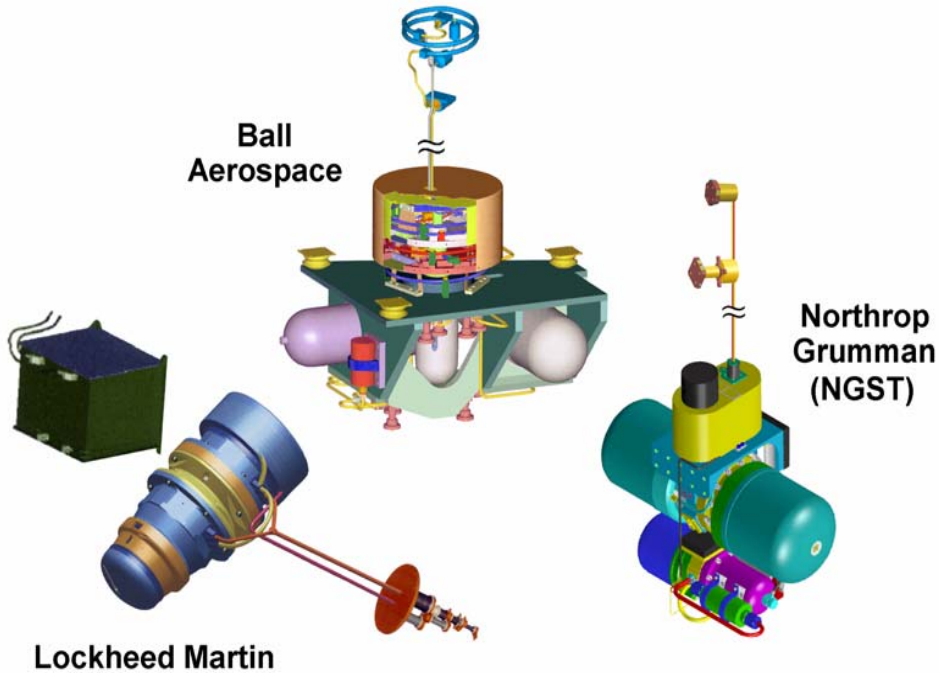
NGST J-T Compressor





NEW Lockheed 4-stage DM Cold Head Assembly

- TPF is developing cryocoolers with 18K/6K cooling stages
- Requirements derived from TPF, JWST, and Constellation-X
- ACTDP will produce three development model coolers (with options for electronics) by 2005
- Three coolers selected for further development: Ball, Lockheed Martin, and Northrop Grumman



Technical Resources at: http://tpf.jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

+ NASA Homepage
+ NASA en Español

JPL HOME | EARTH | SOLAR SYSTEM | STARS & GALAXIES | TECHNOLOGY

PLANETQUEST

Terrestrial Planet Finder

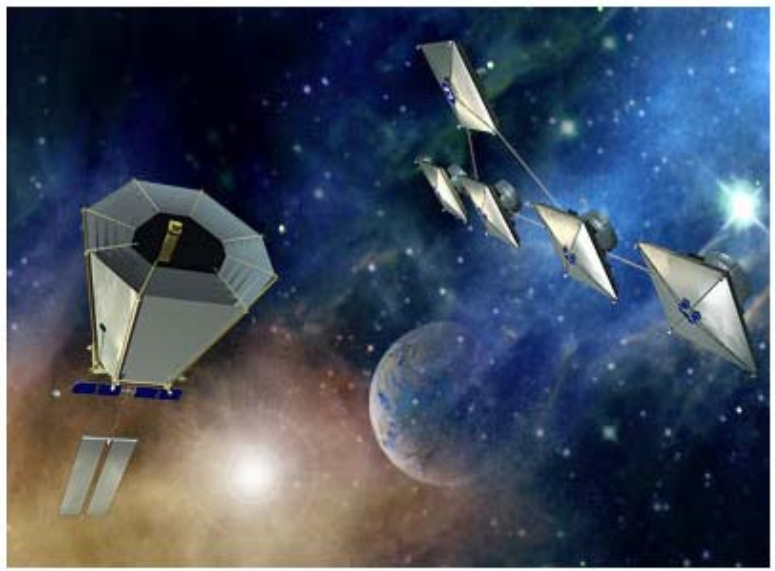
TPF FACTS

TPF NEWS

NASA has issued a TPF-C Proposal Information Package and announced an upcoming pre-proposal conference.
+ Full story

The TPF general astrophysics whitepaper is now available.
+ Download (PDF, 2.1 MB)

NASA has announced the Science Working Group for TPF-I and the Science and Technology Definition Team for TPF-C.
+ Full story
+ Team lists



The **Terrestrial Planet Finder** observatories will study all aspects of planets outside our solar system: from their formation and development in disks of dust and gas around newly forming stars to the presence and features of those planets orbiting the nearest stars; from the numbers at various sizes and places to their suitability as an abode for life.

+ More

TPF OVERVIEW | TPF IN DEPTH | TPF FOR SCIENTISTS ← ***Technical Resources***

TPF Terrestrial Planet Finder