TPF Terrestrial Planet Finder

Terrestrial Planet Finder Coronagraph

Overview of Technology Development & System Design

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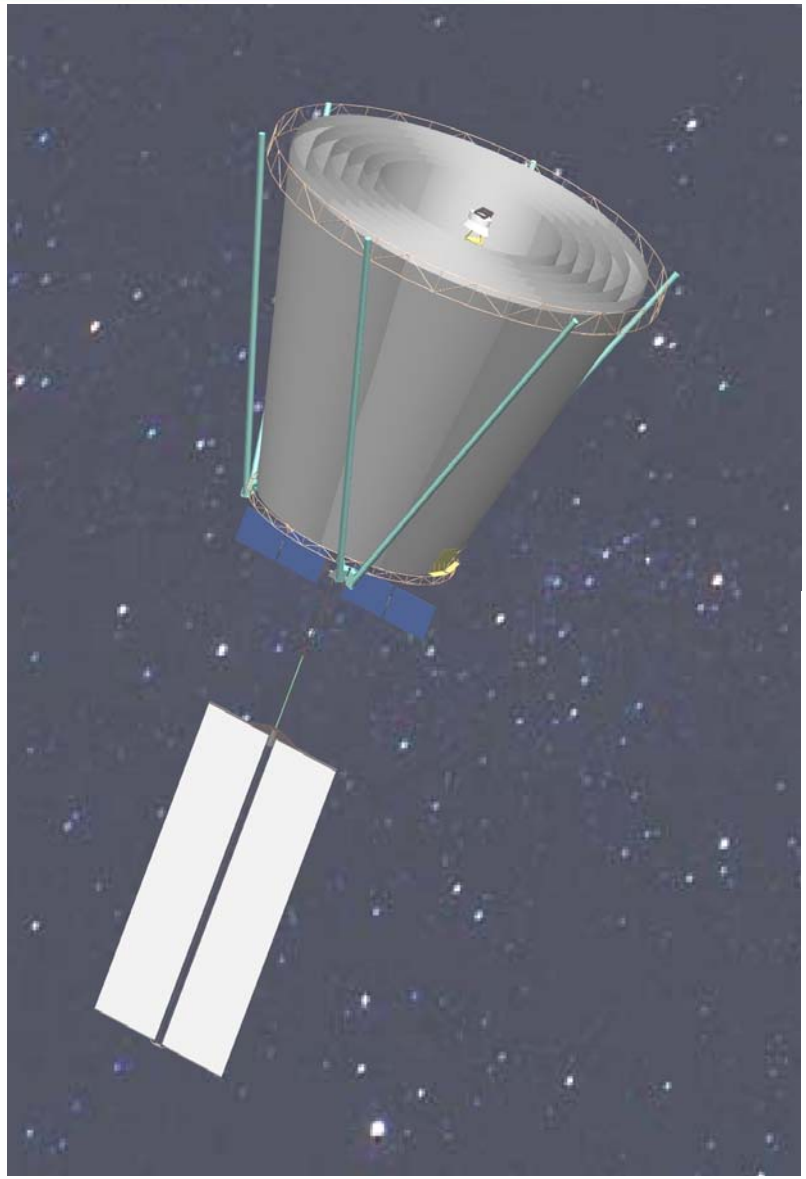
Virginia Ford, Pantazis Mouroulis, Daniel Hoppe and Stuart Shaklan

Representing the work of all the TPF-C personnel

Jet Propulsion Laboratory, California Institute of Technology

7 September 2005



Introduction

Astronomers have discovered over 150 planets orbiting other stars
– "exo-planets"

- NASA mission
  Terrestrial Planet Finder (TPF)

  – Find and characterize terrestrial (or rocky) exo-planets that might harbor life (like Earth)

  – liquid water on the planet (habitable zone)
  – An atmosphere that indicates the presence of life
    - **water, oxygen, ozone, carbon dioxide, chlorophyll, and methane**

- Two missions under development: A coronagraph and an interferometer

- This presentation will focus on TPF coronagraph

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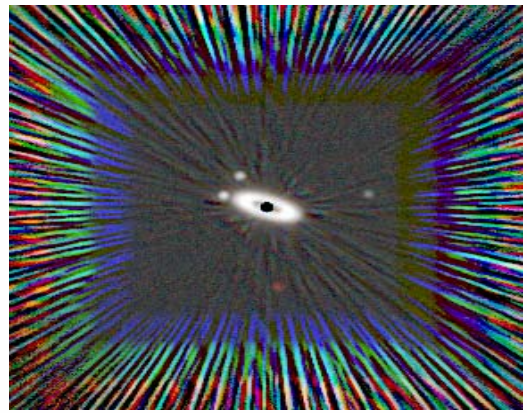
Challenges to optimizing a telescope system to detect and characterize exo-solar planetary systems *(Invited Paper),* J. B. Breckinridge, Jet Propulsion Lab. [SPIE 5875-08]

TPF-C Science Requirements

- Look at stars near earth that might provide an environment that could harbor life
  - roughly 50 stars from a carefully selected list
- Detect earth-like planets in the habitable zone (where liquid water can exist)
  - 90% chance of seeing any planets that are there
  - Goal is to detect and observe planets 10^{-10} times fainter than their parent star
- Extremely tight tolerances on wave front stability
  - Picometer bending of primary mirror
  - Sub nm motion of secondary relative to primary
- If an earth-like planet is detected, characterize its atmosphere so that the presence of life can be detected
  - Spectral range: visible wavelengths from 500 to 800 nm; desired up to 1.05 um
  - Spectral resolution: 70 divisions through range (4.3 nm)



Stapelfeldt

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TPF Coronagraph – specially designed to search for terrestrial planets

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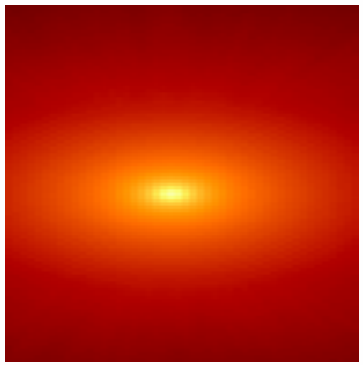
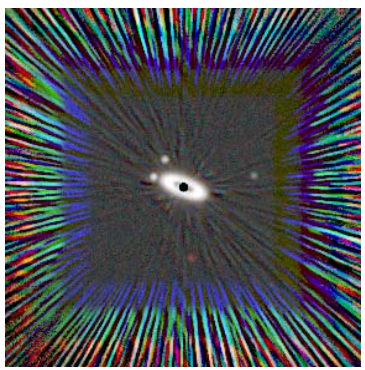
Hubble Space Telescope image of a star

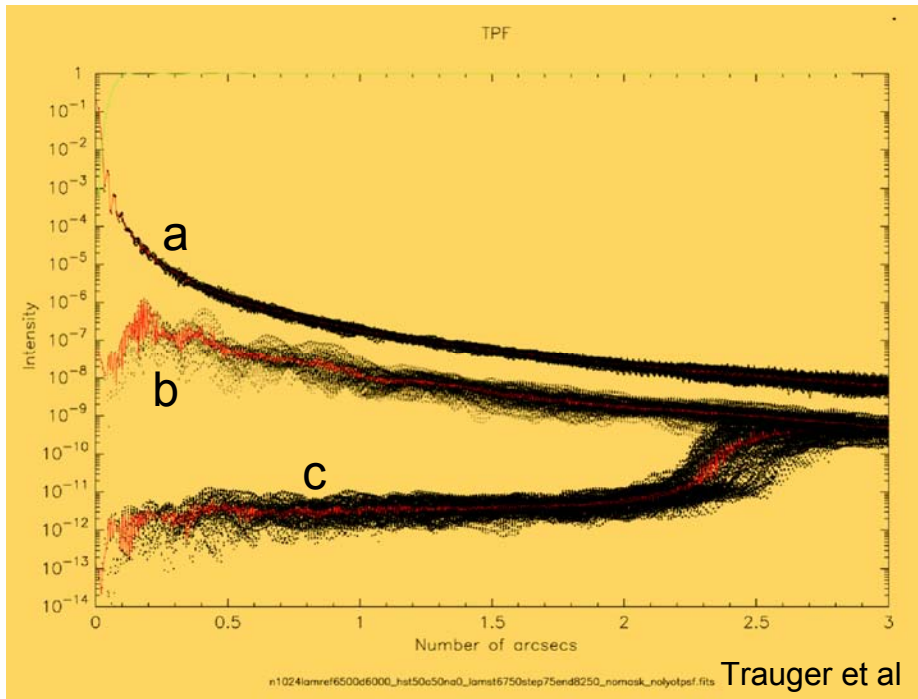
Simulation – unobscured star image after Wave Front Sensing and Correction (WFS&C)



Simulation – image after WFSC & coronagraph



TPF Point Spread Functions: (a) 6x4 m telescope with optics as smooth as Hubble, (b) coronagraph and (c) actively corrected coronagraph



Executive Summary: Optical Design

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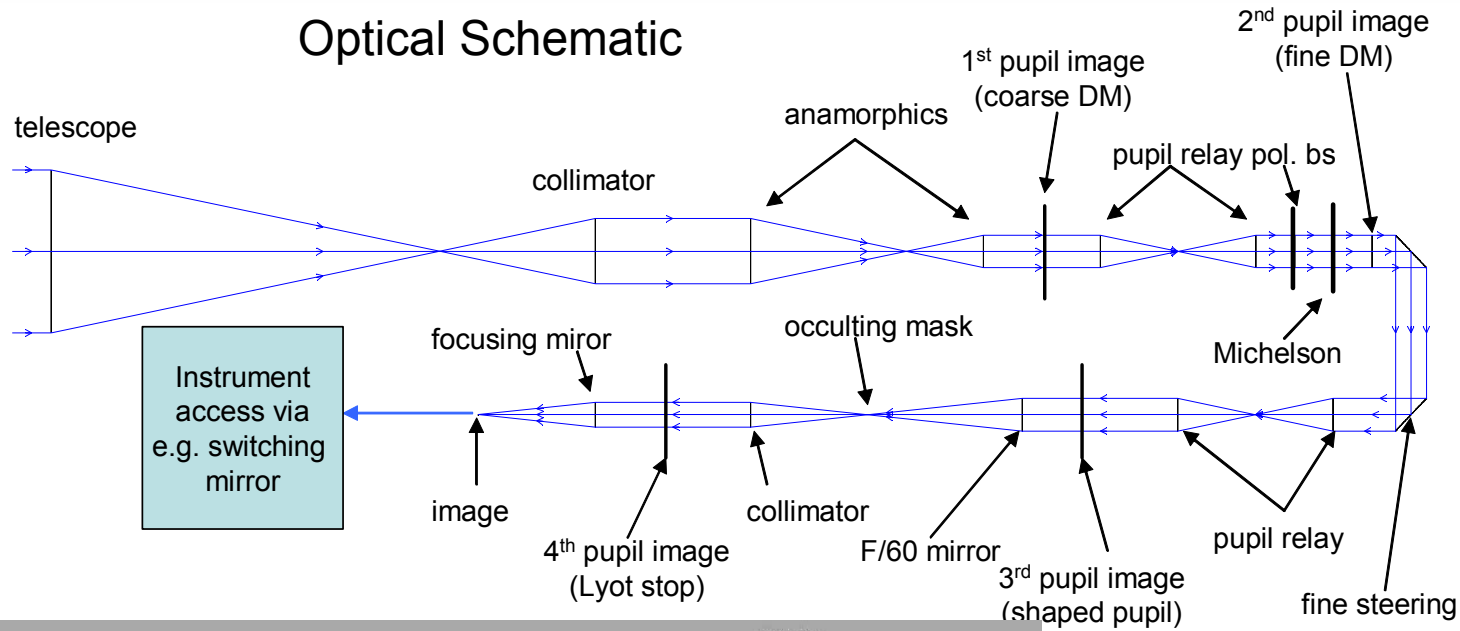
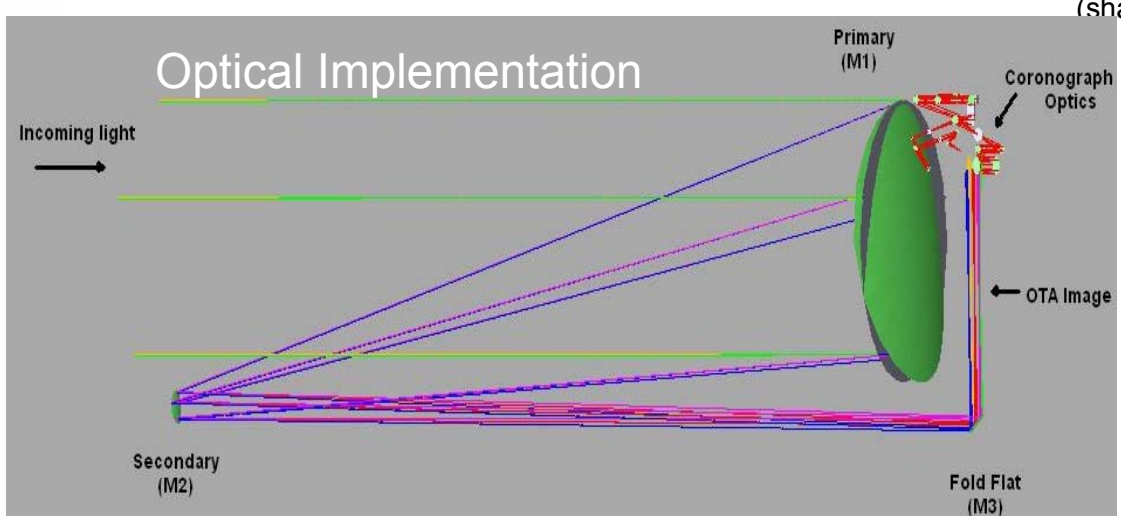
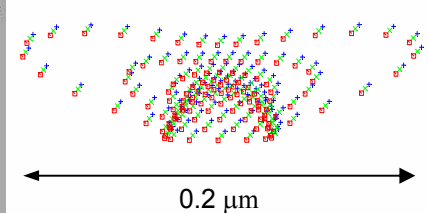
Optical Schematic



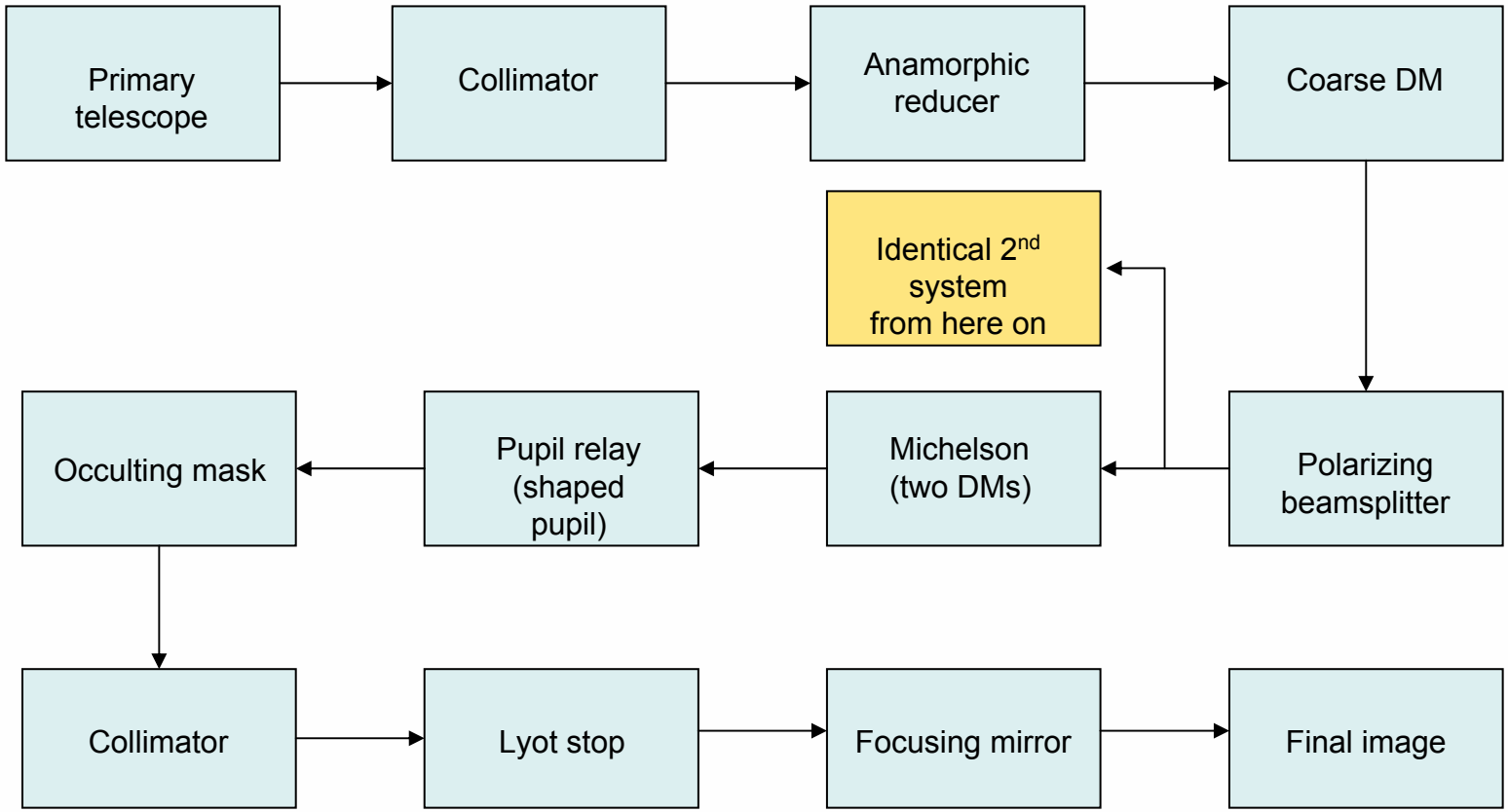
Optical Implementation



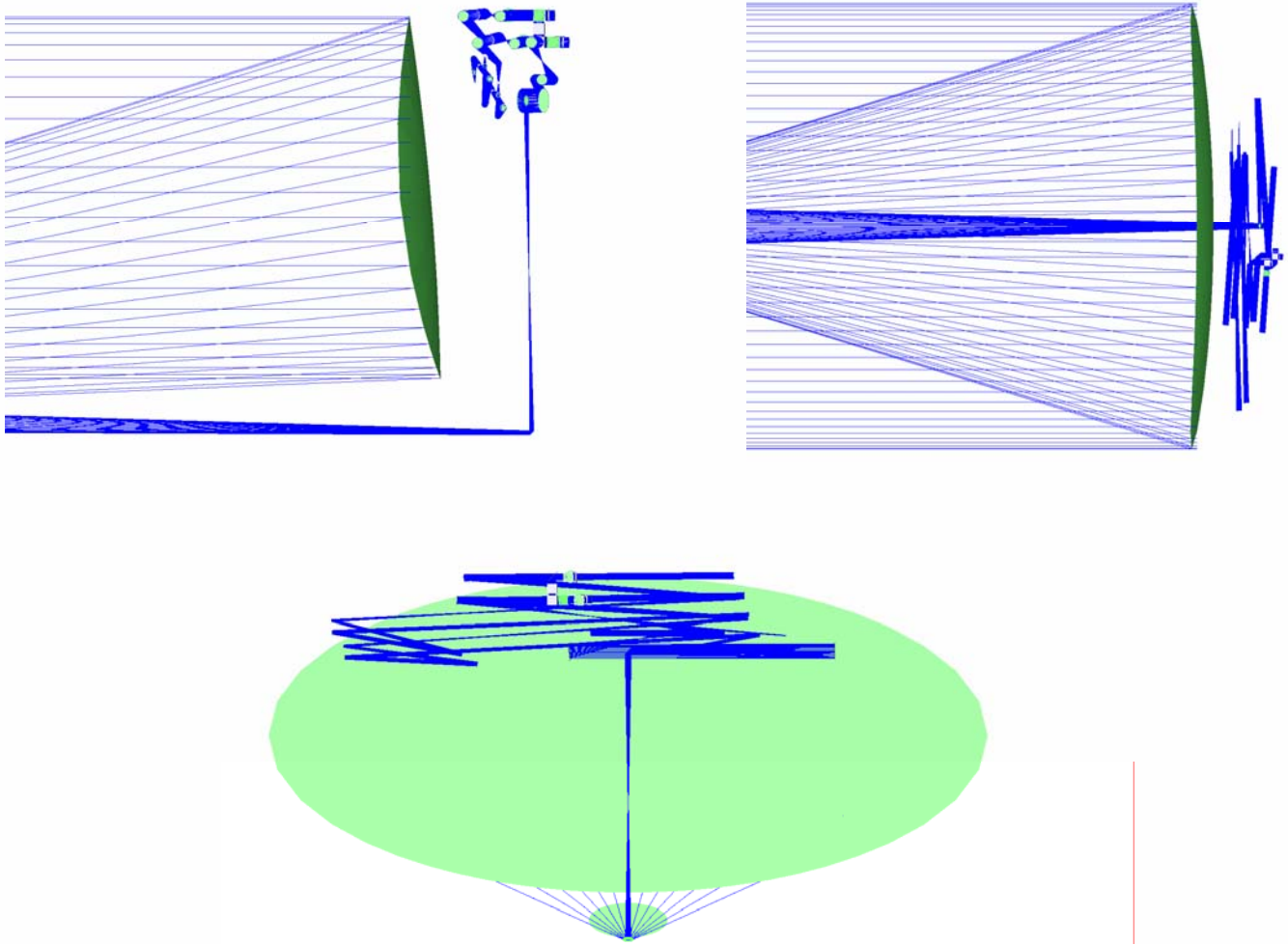
Magnified polychromatic spot diagram at final focus shows chromatic error fully suppressed.



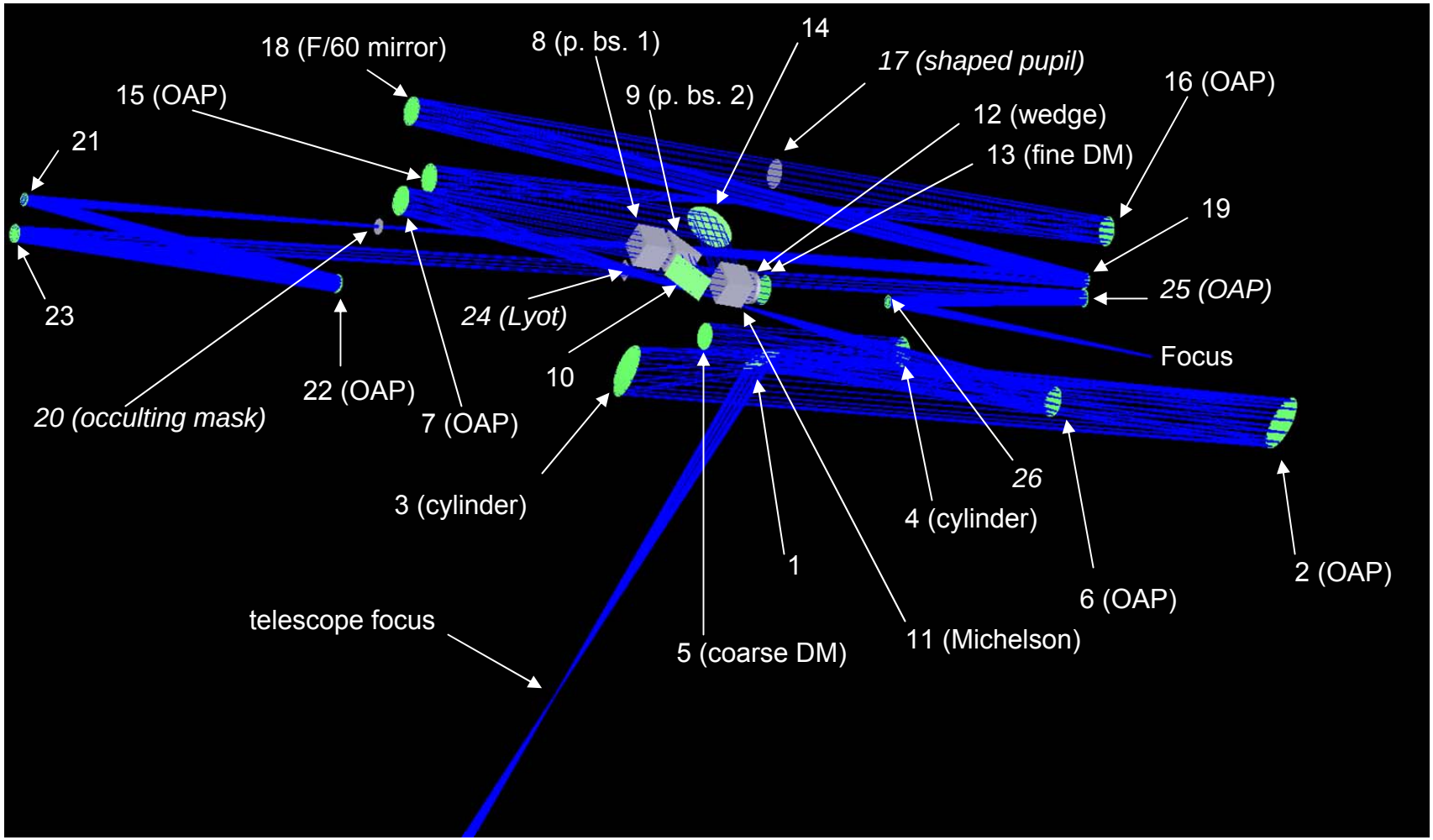
System Block Diagram



Three views of the optics accommodation behind the telescope primary

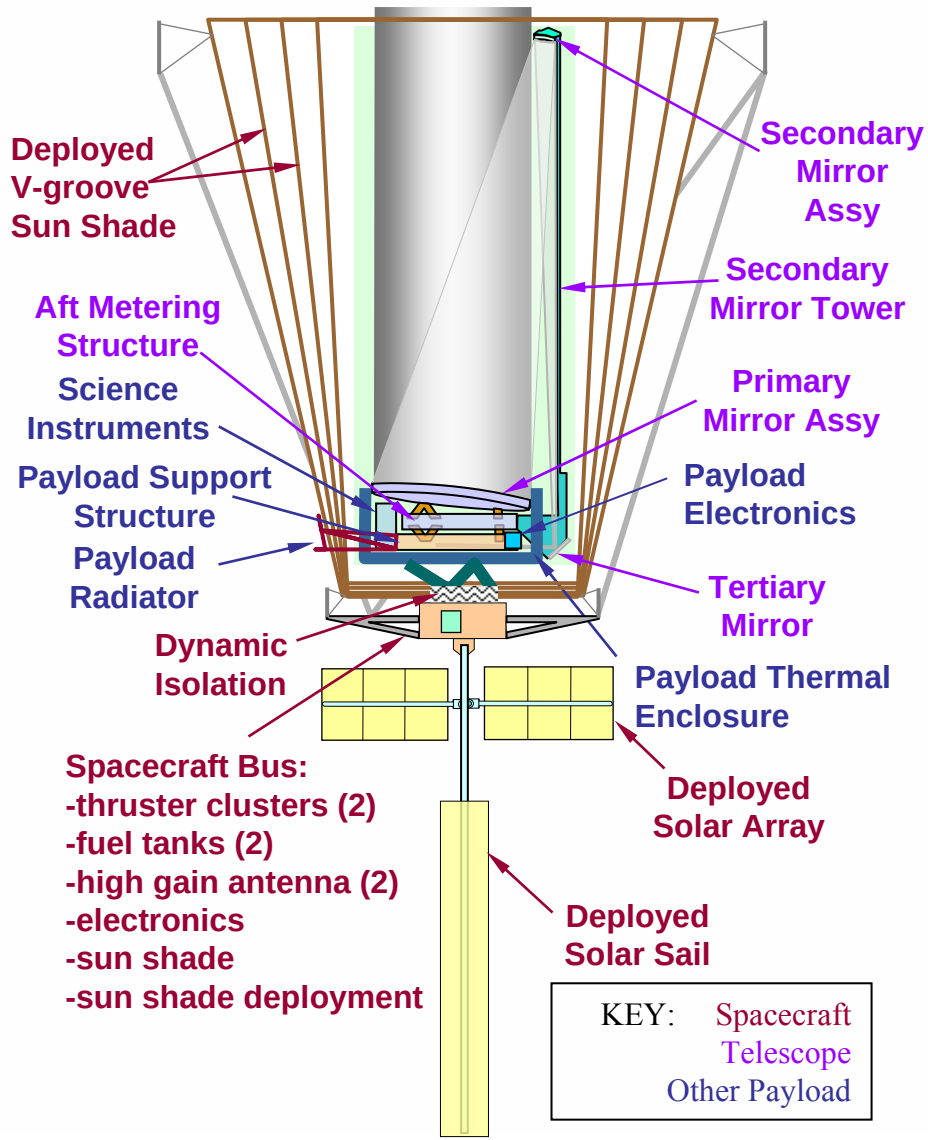


Optical layout (single path)



All powered mirrors are off-axis parabolas (OAP). Elements not otherwise identified are flat fold mirrors. Numbering of elements follows the light (same as table on p. 7.)
Shows one polarization path and a single path through the Michelson (one fine DM).

TPF-C Observatory Concept



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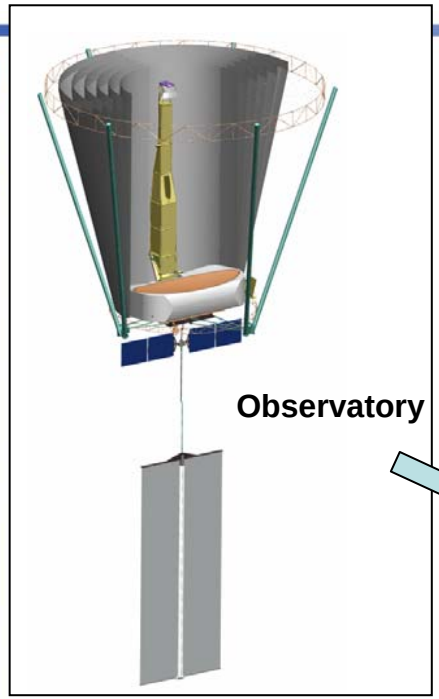
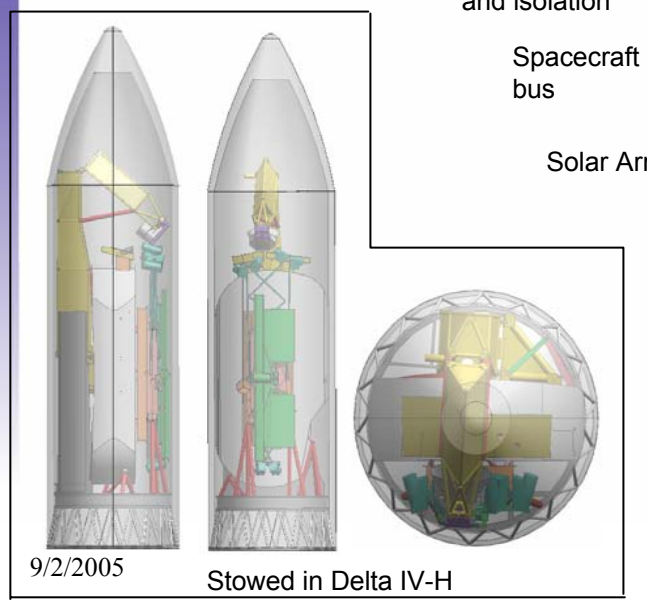
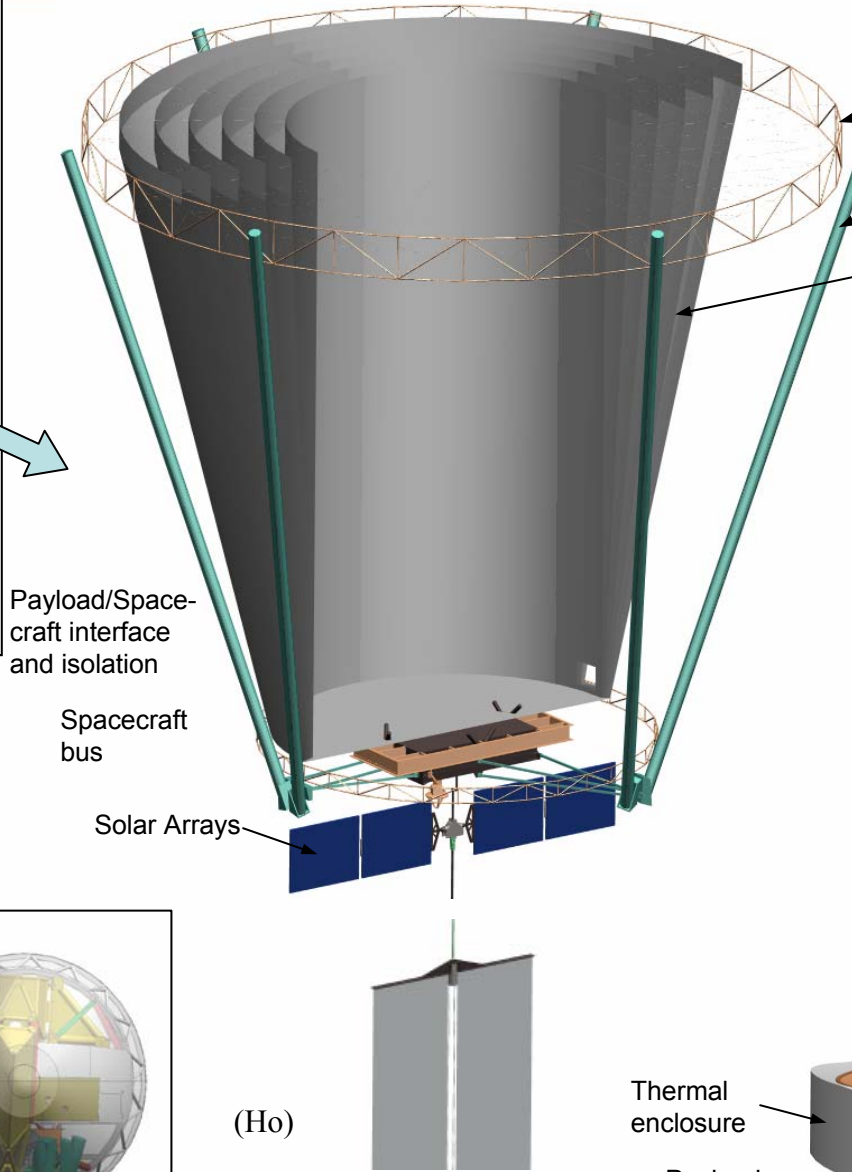
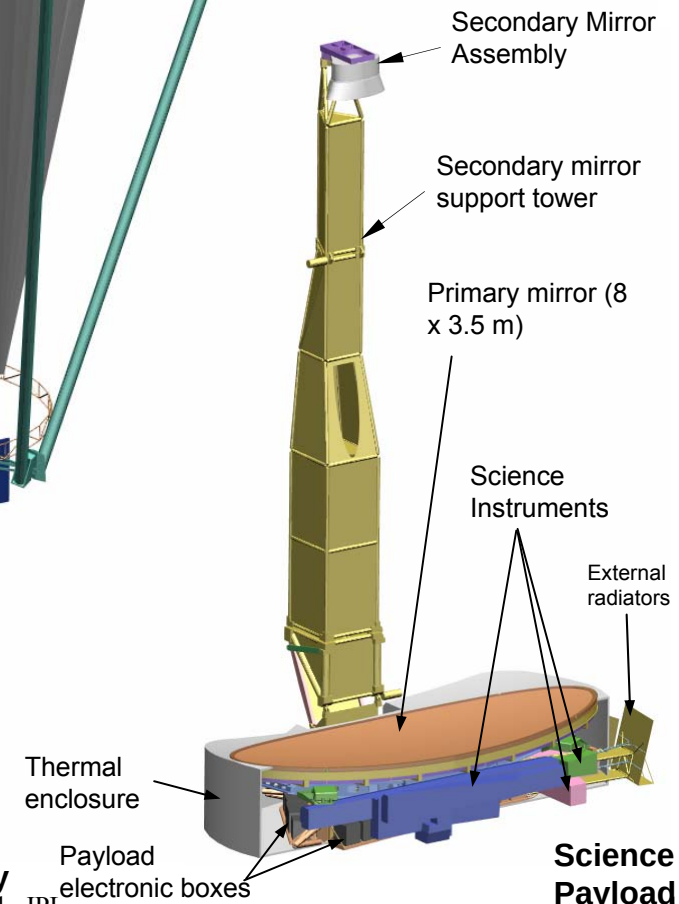
TPF-C System

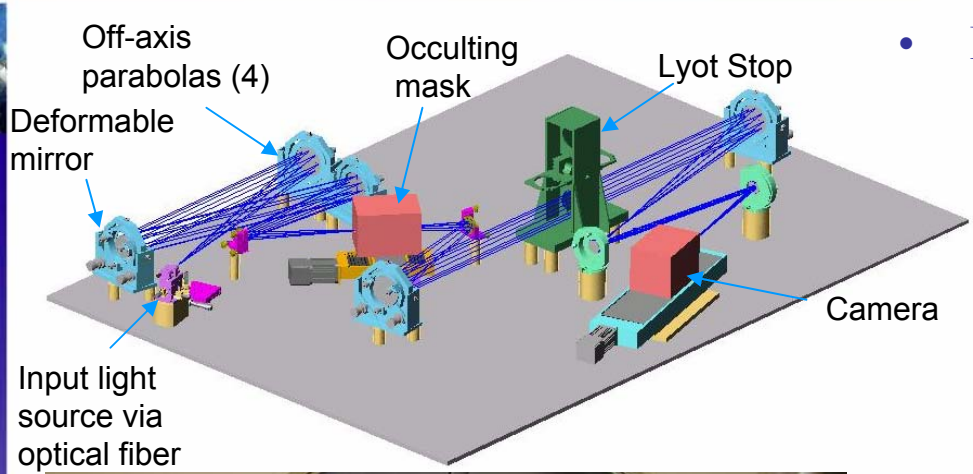

Observatory

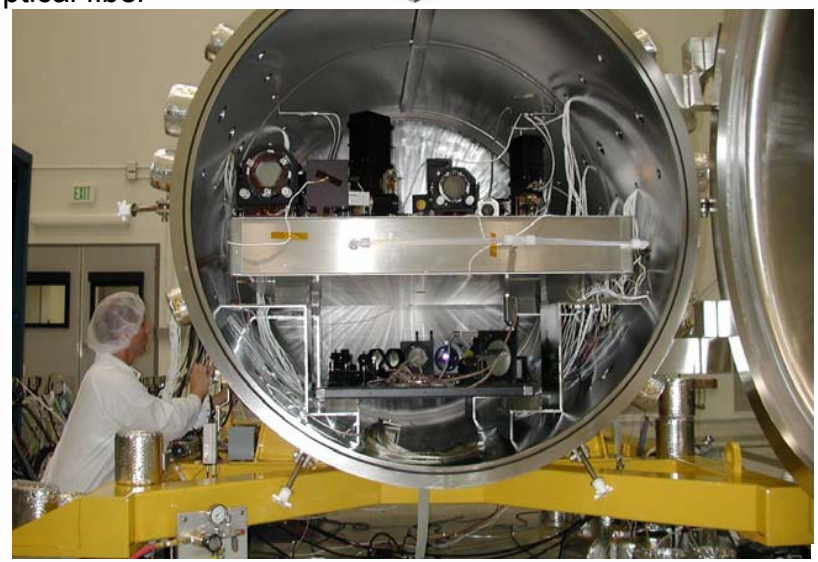

9/2/2005
Stowed in Delta IV-H


V-groove perimeter support truss
V-groove extendible boom
V-groove layers
Payload/Space-craft interface and isolation
Spacecraft bus
Solar Arrays
(Ho)
Spacecraft Assembly


Secondary Mirror Assembly
Secondary mirror support tower
Primary mirror (8 x 3.5 m)
Science Instruments
External radiators
Thermal enclosure
Payload electronic boxes
Science Payload

High Contrast Imaging Testbed

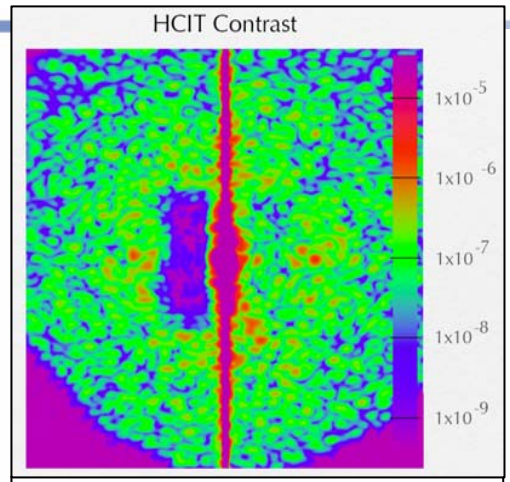




- Demonstrator for starlight suppression
  - Currently set up as a Lyot Coronagraph
  - Dynamically isolated vacuum chamber in controlled laboratory environment – room temp
  - Tests:
    - Deformable mirrors
      - Sequence of maturing devices
    - Algorithms for sensing and controlling wavefront
    - Masks and Stops
  - Demonstrates suppression capability
  - Validates theories and models

Laboratory demonstration of high-contrast imaging technologies and algorithms for space coronagraphy, J. T. Trauger, et al. [SPIE 5905-14]
Optical design of the Terrestrial Planet Finder-Coronagraph, P. Z. Mouroulis, S. B. Shaklan, Jet Propulsion Lab. [SPIE 5874-19]

HCIT and new technology development

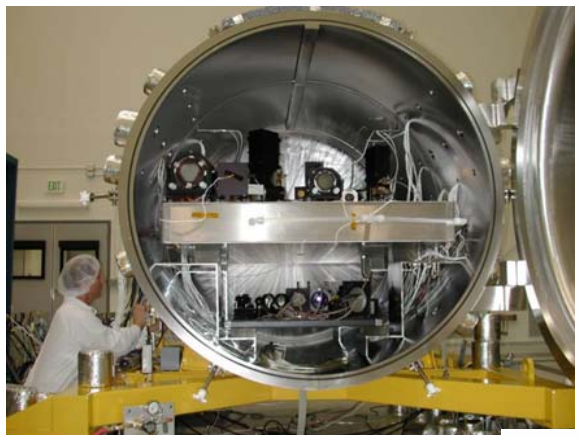


Data by Trauger, Burrows & Moody, HCIT May 2004

Mask Characterization Test Set

Figure 3. Photo of optical setup in dust-free enclosure.

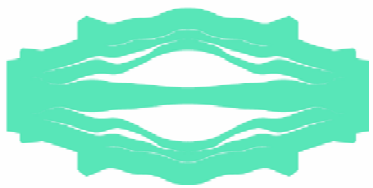
High Contrast Enabling Technology
Xinetics, Inc. Deformable Mirrors
in use in HCIT
Top: 64x64 actuator model
Bottom: 32x32 actuator model

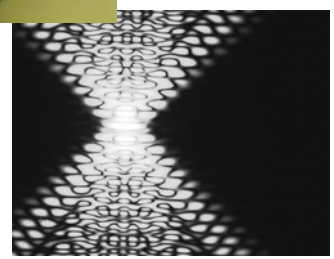


High Contrast Imaging Testbed
Remote Guest Testing in progress
Contrast Results to date: 1.5×10^{-9}

MEMS Deformable Mirrors under TPF development contract with Boston University

Mask Design and Analysis – TPF funded research at JPL, Berkeley, Ball Aerospace and Princeton





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Occulting Focal Plane Masks for Terrestrial Planet Finder Coronagraph

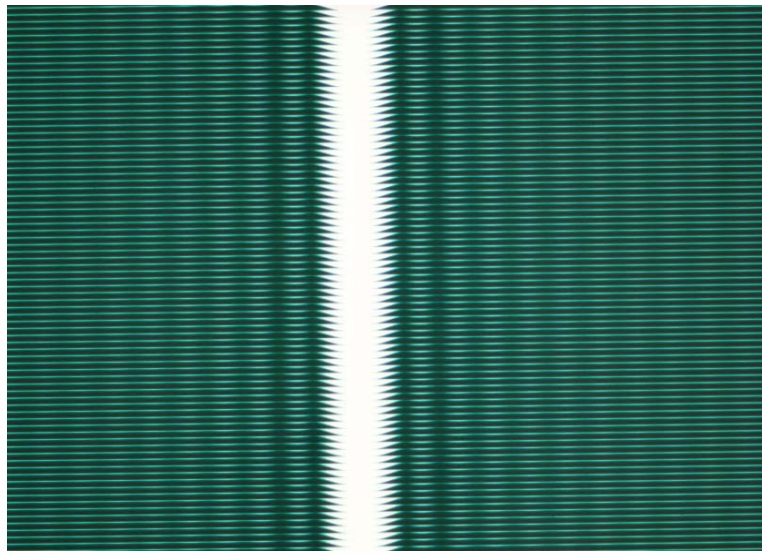
Masks Development

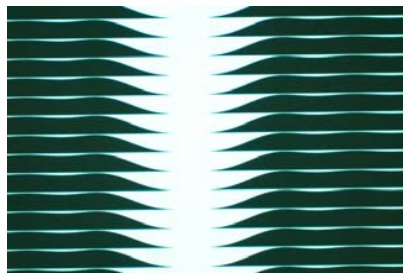
- Design
- Materials
- Process:
  - Theory → Models
  - Material and processes research → fabrication
- New Developments:
  - 8th order mask forms
  - HEBS materials progress

Shaped pupil coronagraphs for planet finding: optimization, manufacturing, and experimental results, N. J. Kasdin, R. J. Vanderbei, Princeton Univ.; J. A. Beall, National Institute of Standards and Technology; R. Belikov, M. G. Littman, M. Carr, Princeton Univ. [SPIE 5905-16]

Coronagraph mask tolerances for exo-Earth detection, O. P. Lay, J. J. Green, D. J. Hoppe, S. B. Shaklan, Jet Propulsion Lab. [SPIE 5905-18]

P. Halverson, et al., Measurement of wavefront phase delay and optical density in apodized coronagraphic masks materials [SPIE 5905-53]





Microscope photos of 8th order binary mask - black is clear, white is coating

(Balasubramanian)

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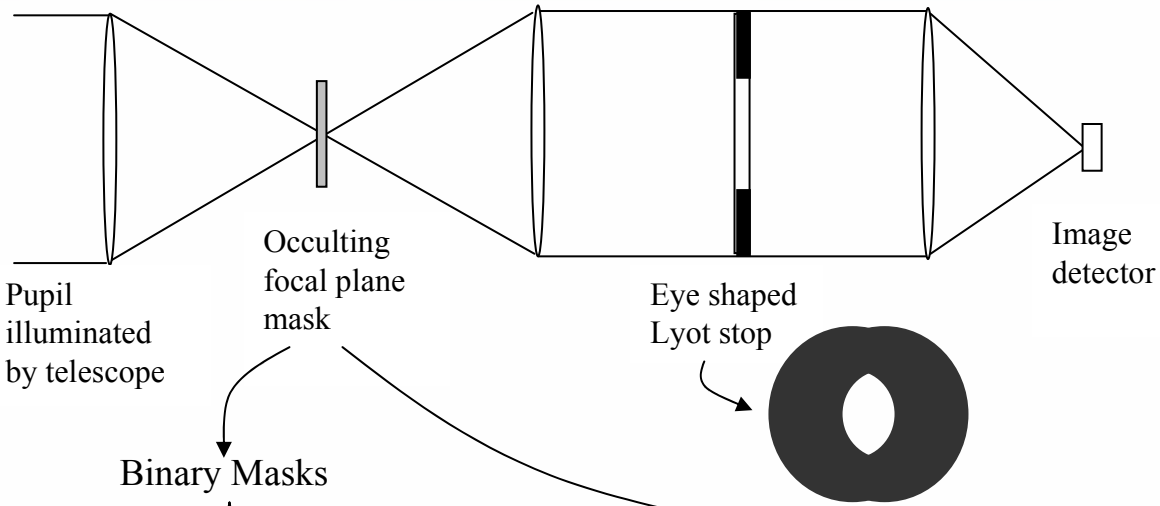
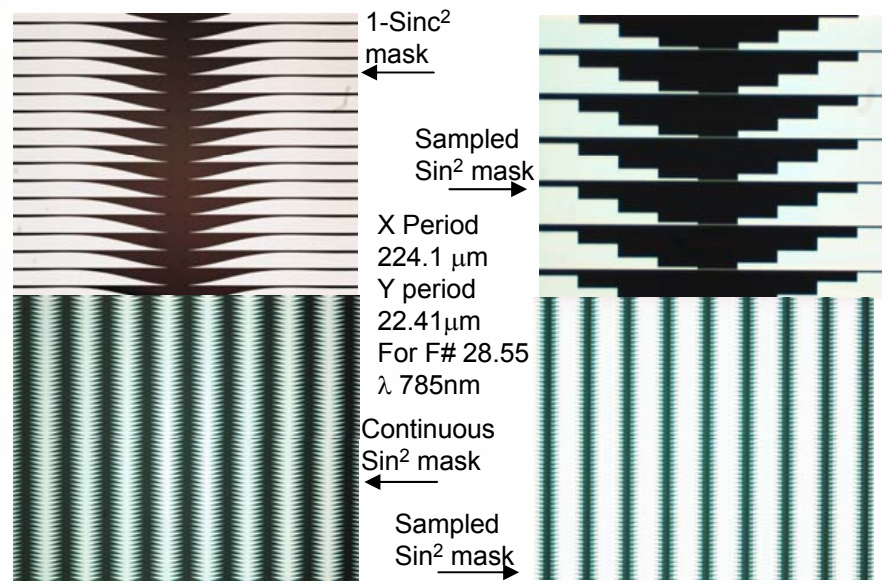
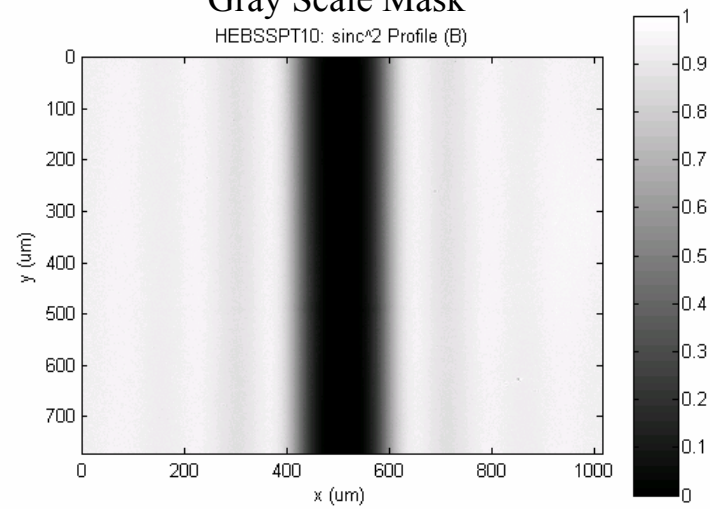
TPF Lyot Coronagraph Conceptual Model



Binary Masks



Gray Scale Mask



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Mask Technology Demands

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Technology Challenges

- **Precision masks for Coronagraphy**
  - 10^{-10} level star light suppression required for exoplanet detection
  - Broadband performance required for planet characterization
  - Polarization neutrality required for system performance
  - Durability and stability required over mission life
  - Practically realizable technology

Candidate Technologies

- **Focal plane masks with Lyot stops**

  - Absorptive HEBS (High Energy Beam Sensitive) glass masks

  - Diffractive binary masks

- **Pupil plane masks and combinations**

  - Two dimensional bar code type metal on glass masks

  - Other shaped masks

  - Etched Si masks

Mask Technology Goals

- Design, Fabricate, Characterize and Test various masks
  - Characterize and understand material properties
  - Design and model device performance
  - Perfect fabrication processes to meet specs
- Test masks in HCIT (High Contrast Imaging Testbed)
  HCIT is a test coronagraph in a large vacuum chamber
- Iterate and validate technology needed for masks to achieve required contrast of 10^{-10} over the required bandwidth

HEBS Gray Scale Mask Design

The specified mathematical profiles for gray scale masks:

Profile (c)

$$T(x) = T_0\left[1-\left(\frac{\sin(\pi x/w)}{(\pi x/w)}\right)^2\right]^2$$

Note: w = 157.7 μm
$T(x) = 0.5\ T_0$ at $x = 90.3$ μm
Set $T(x) = 1.0$ for all $|x| >$ 1.1 mm

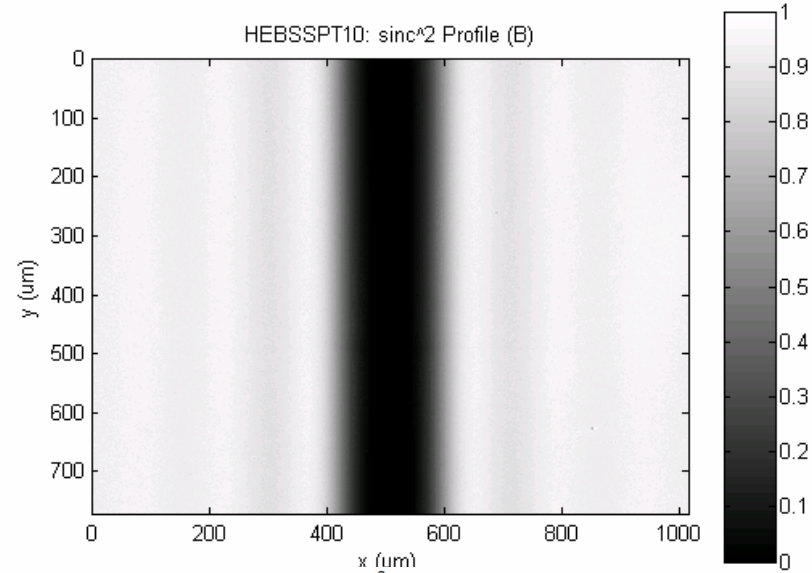
Profile (d)

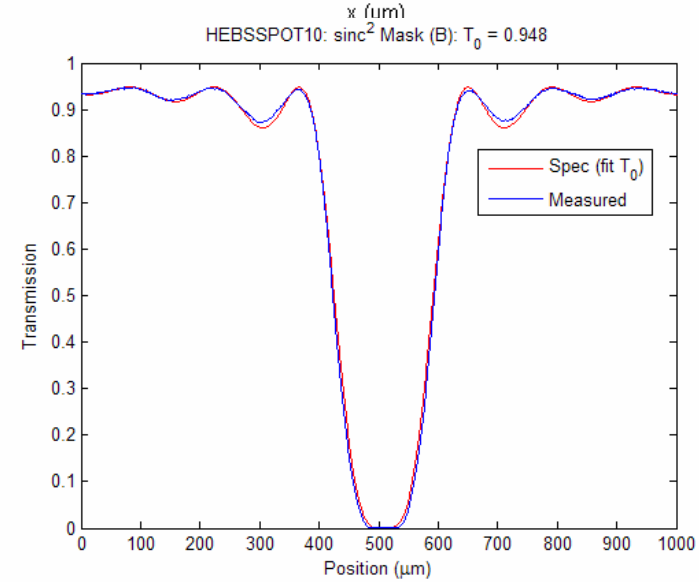
$$T(x) = T_0\left[1-\left(\frac{\sin(\pi x/w)}{(\pi x/w)}\right)^2\right]^2$$

Note: w = 118.2 μm
$T(x) = 0.5\ T_0$ at $x = 67.7$ μm
Set $T(x) = 1.0$ for all $x >$ 946 μm

These profiles were designed for F# 28.55 and wavelength 785nm

Note: High Energy Electron Beam Sensitive (HEBS) glass Produced by Canyon Materials, Inc. San Diego CA. USA. http://canyonmaterials.com





Binary Mask Design

$$h(x) = P_y\left[1-\sqrt{T_0}\left(1-\left(\frac{\sin\left(\frac{\pi x}{w}\right)}{\left(\frac{\pi x}{w}\right)}\right)^2\right)\right]$$

$$T_0 = \sqrt{0.9}$$

$$-4.0mm < y < 4.0mm$$

$$P_y = F * \lambda = 22.4\mu m$$

$$h_{\min} = P_y\left[1-\sqrt{T_0}\right] = 1.15\mu m$$

Mask #1 (pattern 3 in layout):

$$w = 157.7\mu m$$

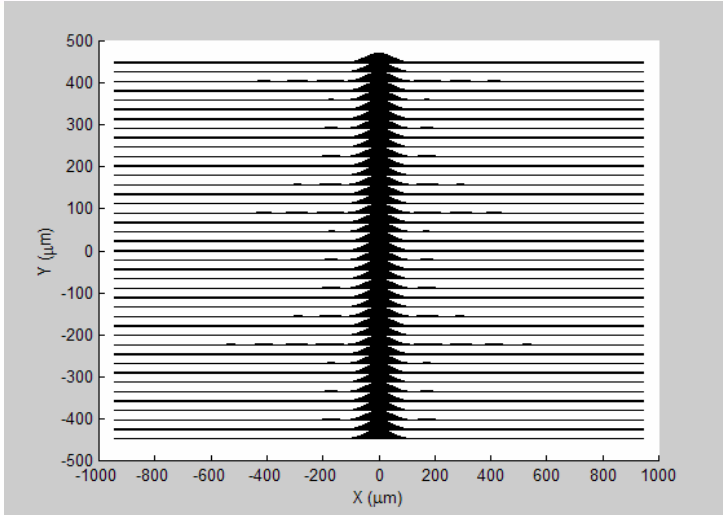
$$-7 * w < x < 7 * w$$

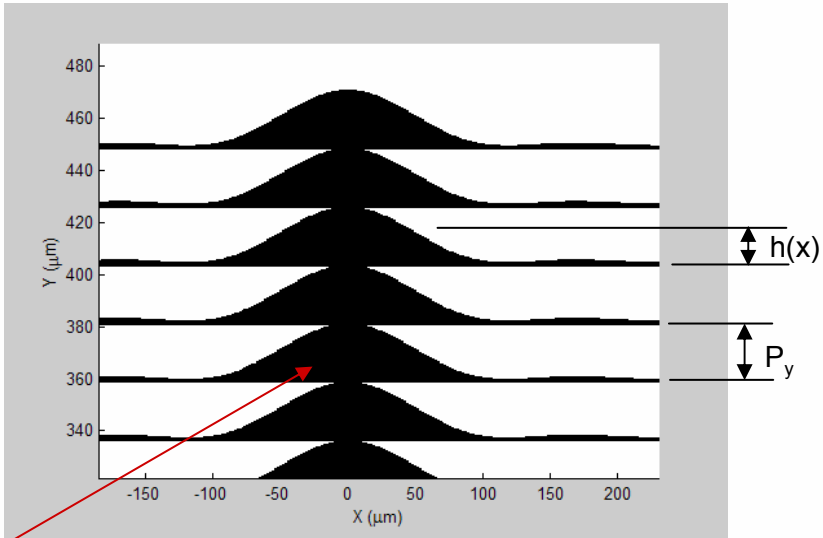
Mask #2 (pattern 6 in layout):

$$w = 118.2\mu m$$

$$-8 * w < x < 8 * w$$

Field transmission for the zeroth-order diffracted wave is simply proportional to the local gap. Higher order diffracted waves are blocked by the Lyot stop





Opaque regions with nominally 150nm thick aluminum

HEBS mask fabrication

Mask pattern locations:

a) Fiducial mark, a pair of 10μm-wide lines in the form of a '+'
b) Blank
c) Linear $sinc^2$ profile (c), with pattern length of 8 mm
d) Linear $sinc^2$ profile (d), with pattern length of 8 mm
e) Fiducial mark, a pair of 10μm-wide lines in the form of a '+'

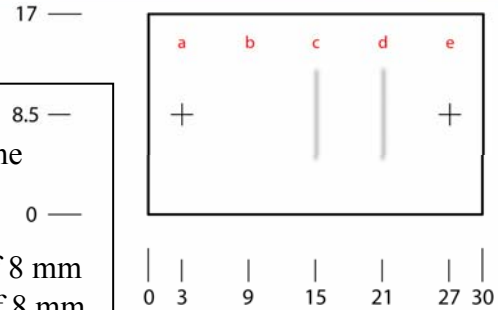
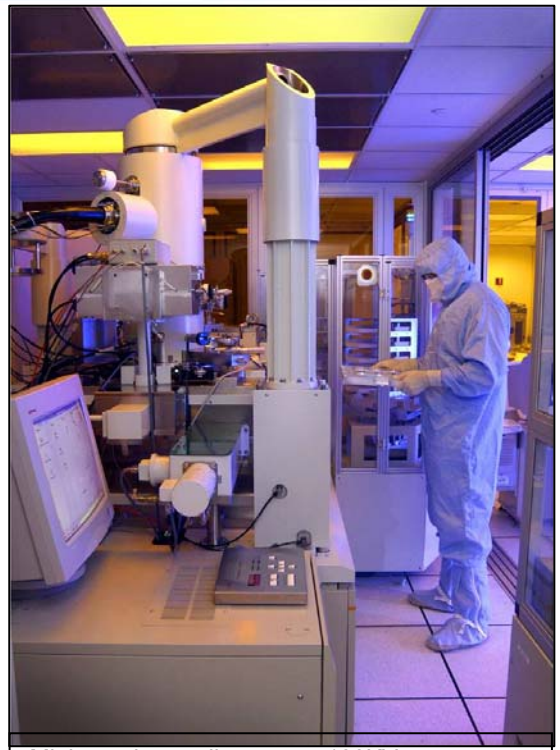


Figure . HEBS mask patterns layout on a 17mm x 30mm HEBS glass

Fabrication Process:

- Thermally evaporate a thin layer of chrome to serve as an E-beam discharge layer
- E-beam expose pattern with the following parameters:
  Acceleration voltage = 100kV
  Current = 1 nA
  Spot-to-spot step size = 50 nm
  Spot size ≈ 150 nm
- Remove chrome in Chromium Etchant
- Clean plate in Alconox detergent and rinse with deionized water.



Minimum beam dia: 4nm at 100KV

Electron beam vector scanning with scan increments down to 1nm

Laser interferometer positioning system with a resolution of 0.62nm

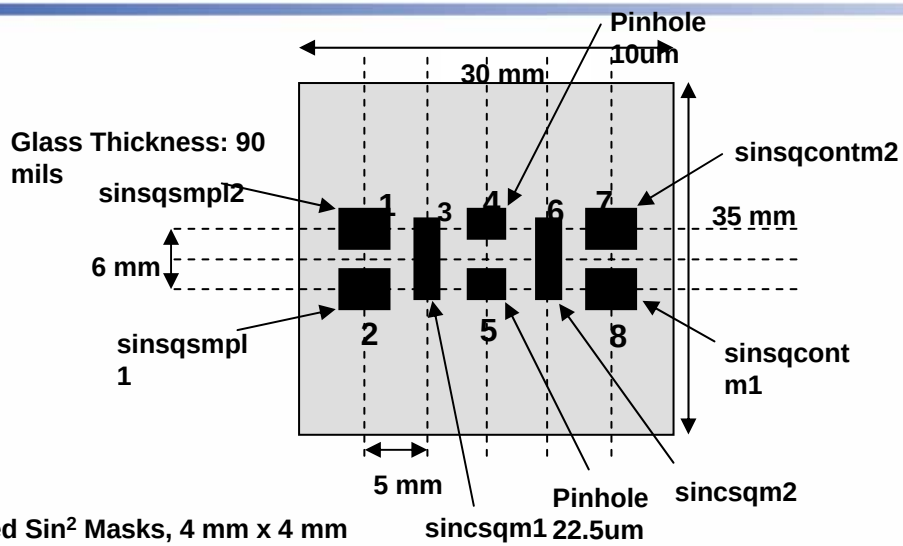
Stitching accuracy between fields better than 20nm.

The acceleration voltage switchable between 50kV and 100kV

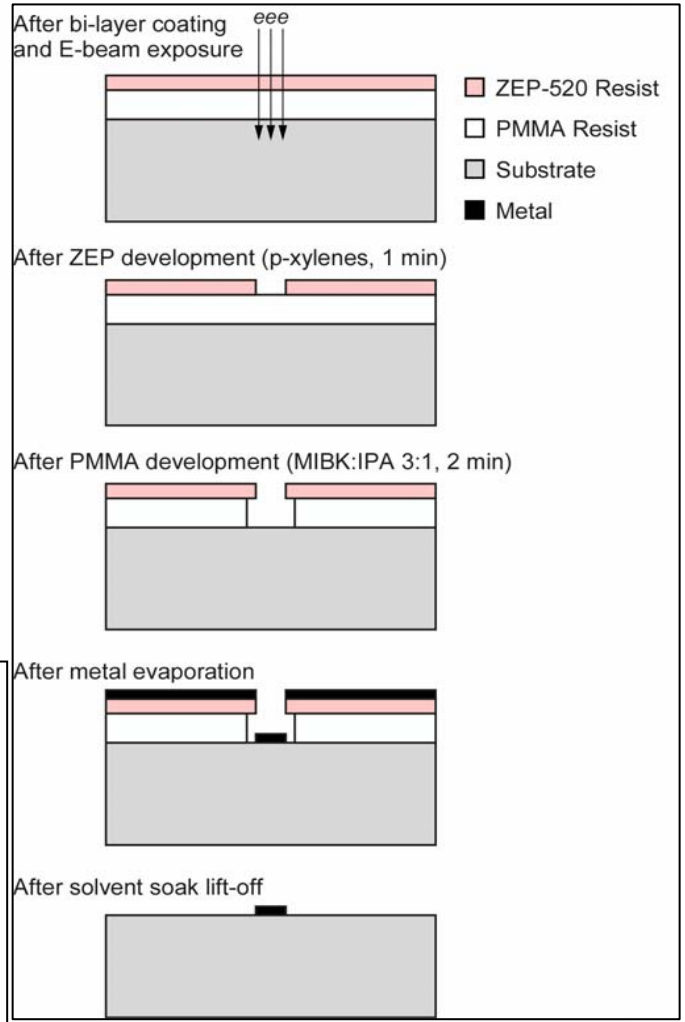
Figure. E-beam Lithography system employed to fabricate masks at MDL

- Trauger *et al*., Coronagraph contrast demonstrations with the High Contrast Imaging Testbed, SPIE 5487, (2004), pp. 1330-1336
- Wilson *et al*., Eclipse apodization: realization of occulting spots and Lyot masks, SPIE 4860, (2003), pp. 361-370
- Halverson *et al*., Measurement of wavefront phase delay and optical density in apodized coronagraphic mask materials, SPIE 5905, (2005)

Binary mask fabrication



1,2: Sampled Sin^2 Masks, 4 mm x 4 mm
3: 1-$Sinc^2$ Mask Design #1, 2 mm x 8 mm
4,5: Pinholes, D=10.0 and 22.5 µm, 3 mm x 3 mm
6: 1-$Sinc^2$ Mask Design #2, 2 mm x 8 mm
7,8: Continuous Sin^2 Masks, 4 mm x 4 mm



E-beam patterning

A 90mil thick fused silica substrate is coated with PMMA 950K to a film thickness of about 200 nm. A top layer of resist, 100 nm of ZEP 520 is applied. Finally, a 20 nm thick Al discharge layer is evaporated on top of the resist structure. The sample is exposed in the JEOL 9300 electron beam lithography system. After exposure, the Al discharge layer is removed in AZ400K resist developer. The pattern is developed with p-Xylenes followed by MIBK:IPA 3:1 to develop the PMMA underlayer. The resist bilayer creates an undercut profile to facilitate lift off. The substrate is then placed in the thermal evaporator and 150 nm aluminum is deposited. The last step is the lift-off in acetone to get the required binary mask pattern.

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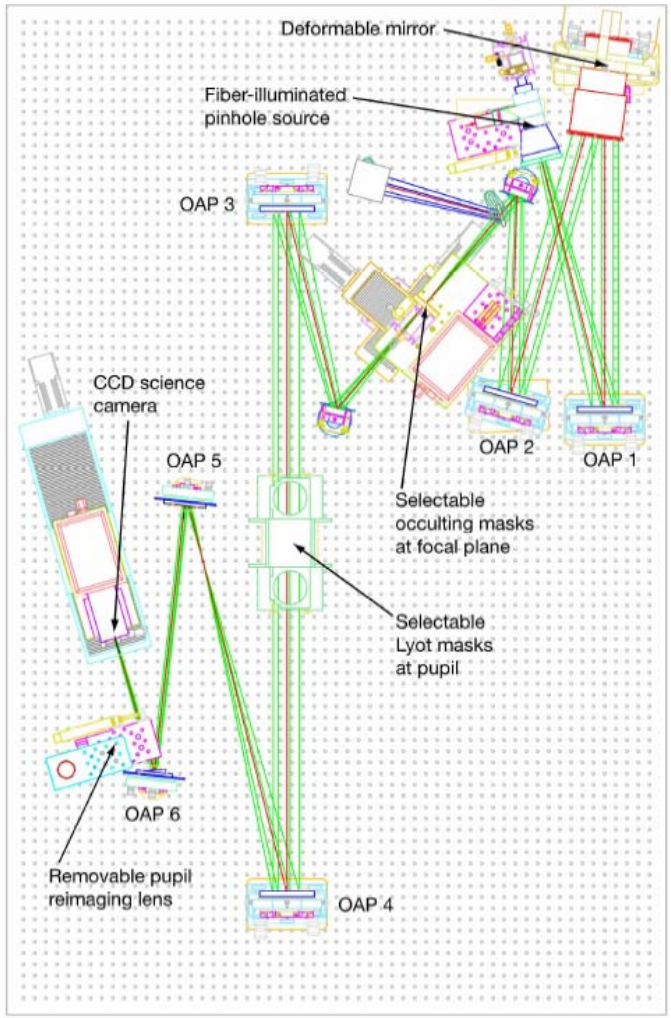
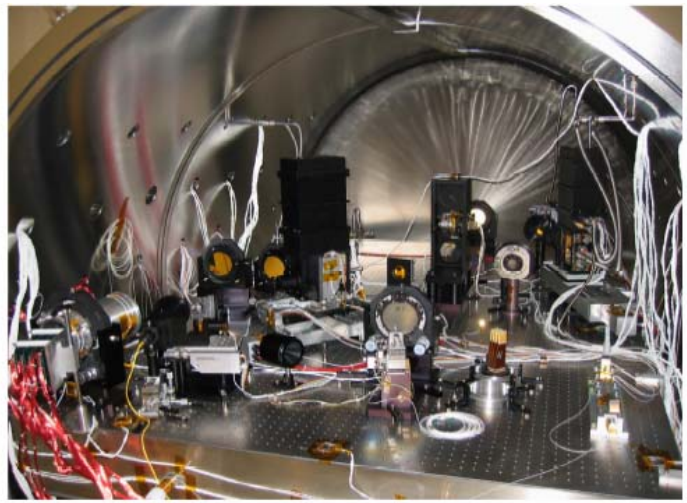
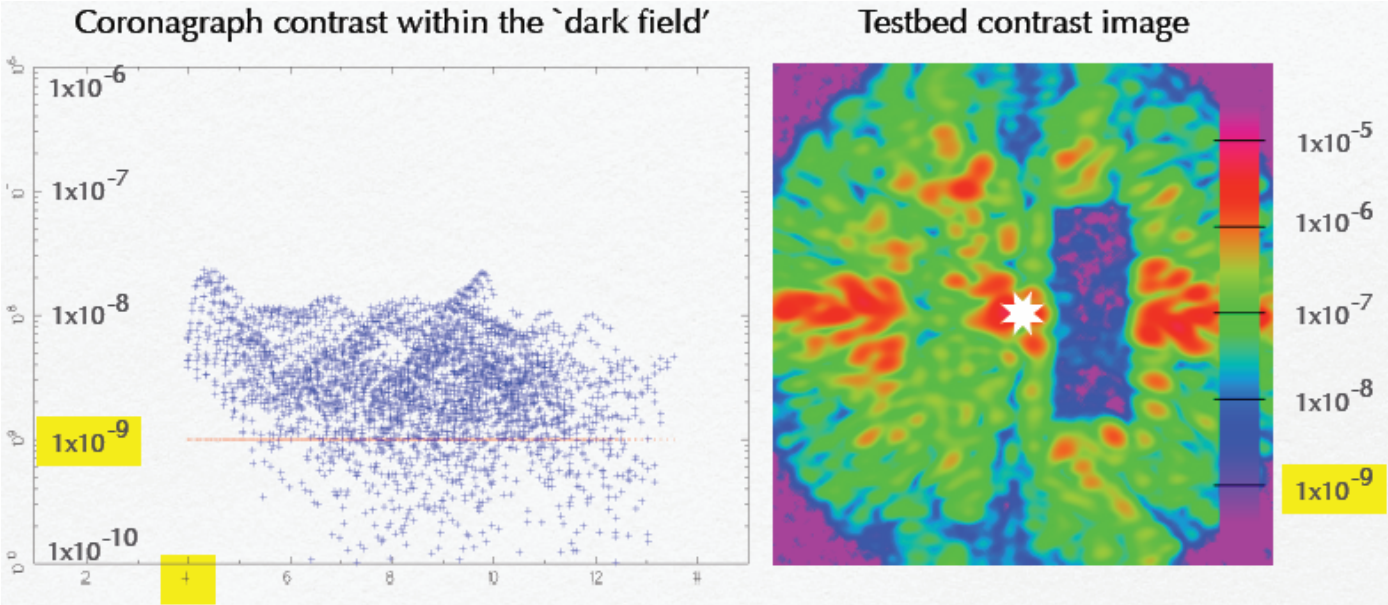
High Contrast Imaging Test Bed at JPL





Results with HEBS Mask



This laboratory coronagraph image was obtained with a linear occulting mask in February 2005. Inner boundary of the target box is 4 Airy radii to the right of the suppressed `star' image (star position is indicated by the star-shaped fiducial). Average intensity of background speckles in the target box is fainter than the `star' by a factor of 3×10^{-9} in 800 nm filtered white light (10% bandpass, 760-840 nm).

Figure. HCIT Contrast vs Airy radius in the target box of 4 to 10λ/D in x and - 10 to +10λ/D in y

Results with Binary Mask

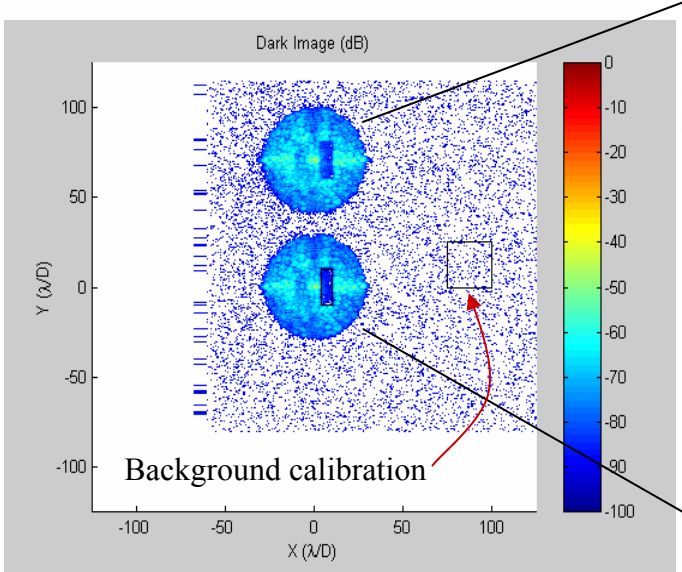


Figure a. Final images (Experimental) showing the two polarizations and the corresponding contrast plots from experimental data

The experimentally measured average contrast in the polarization being nulled is 4.3×10^{-9}, whereas the average contrast in the orthogonal field not nulled by DM is 1.9×10^{-8}.

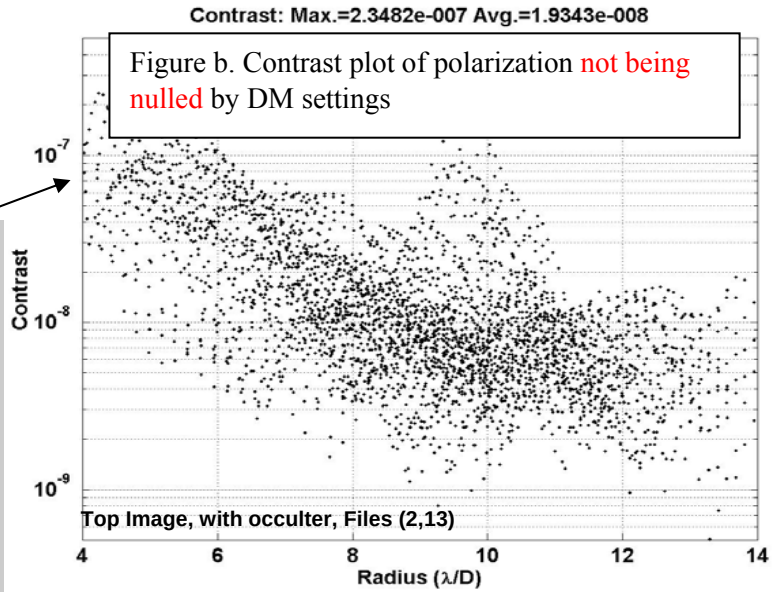


Figure b. Contrast plot of polarization not being nulled by DM settings

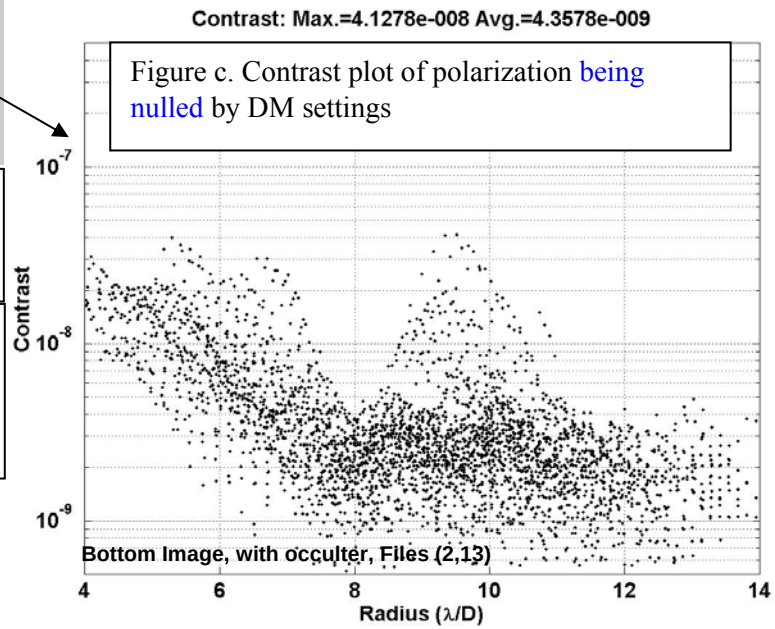


Figure c. Contrast plot of polarization being nulled by DM settings

Simulations

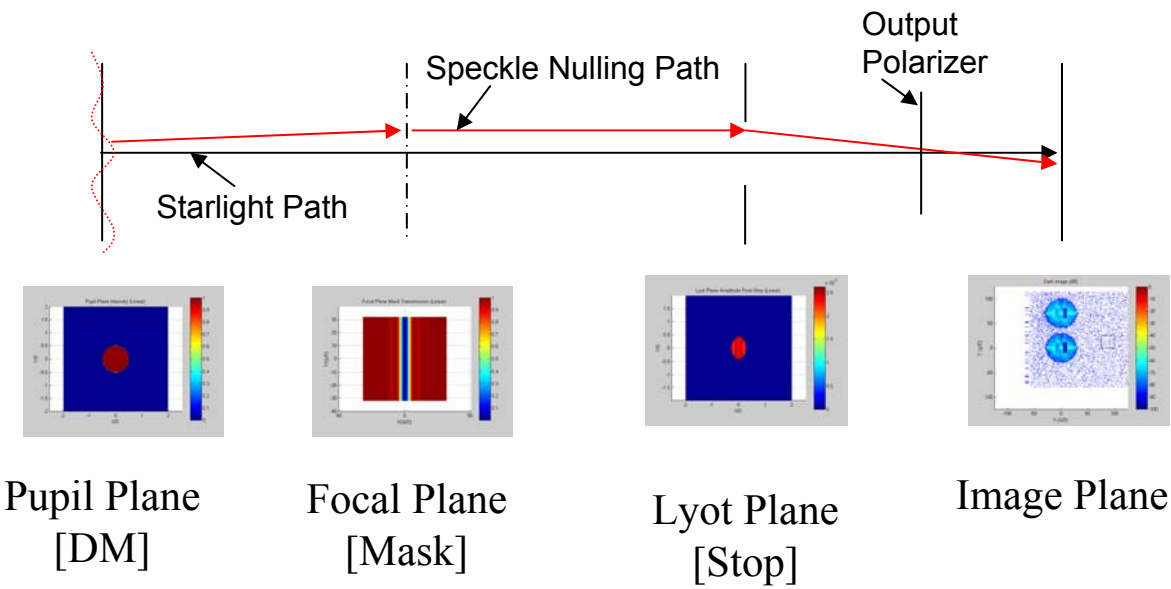
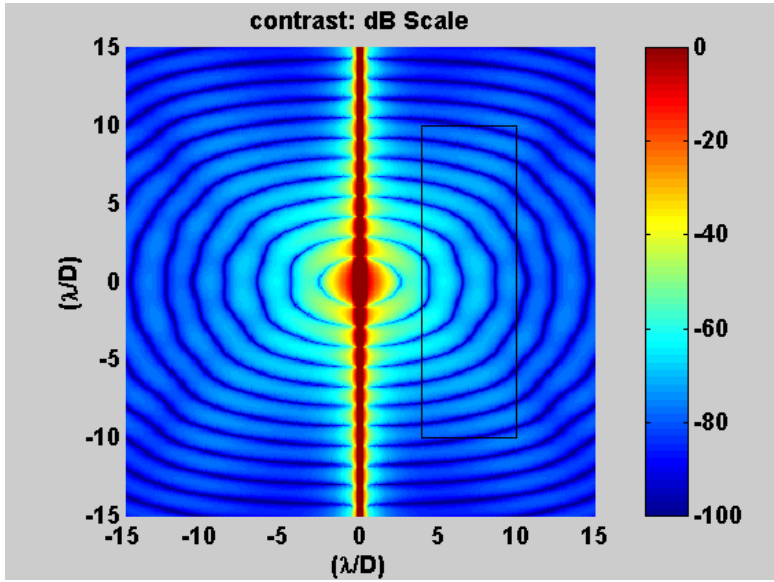


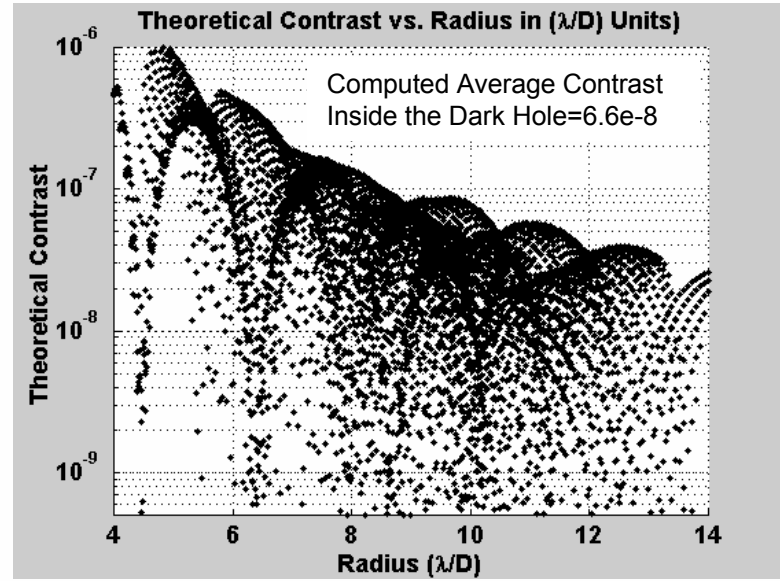
Figure. Conceptual layout of the coronagraph resembling the HCIT for theoretical simulation of contrast at the final image for the two orthogonal polarization states

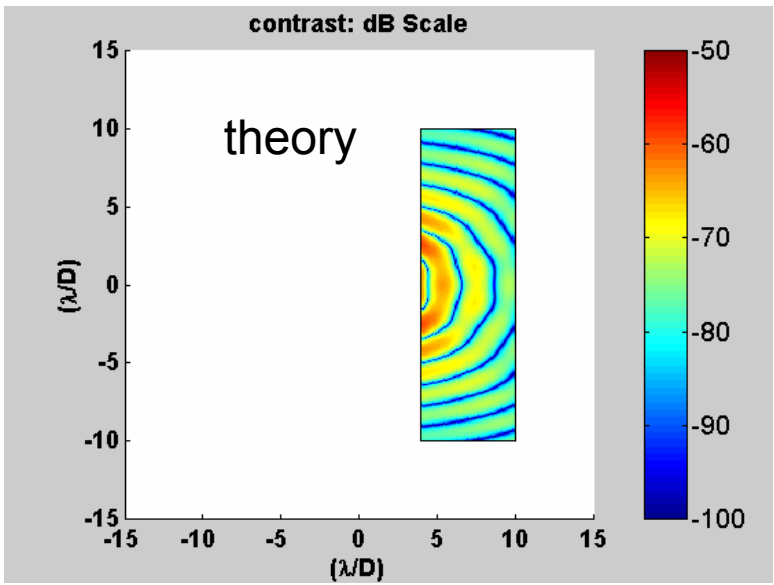
<u>Assumptions for the theoretical simulation:</u>

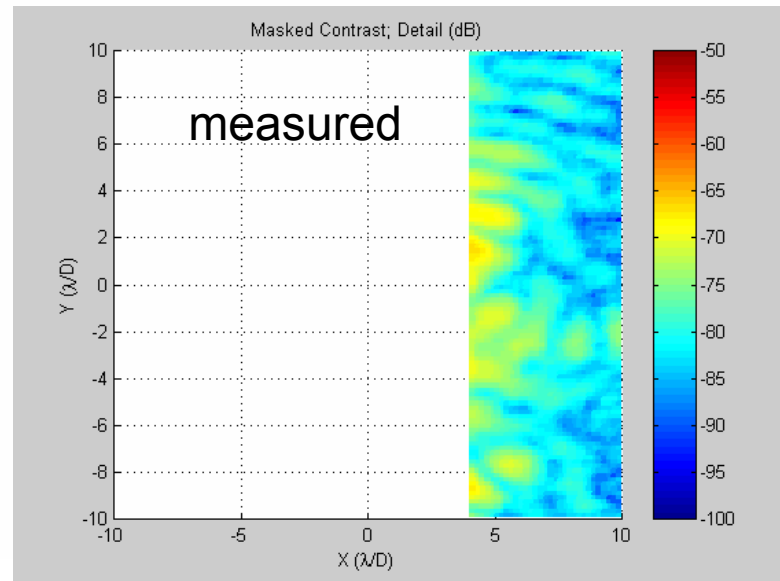
Input polarization is wandering in time.
Images for each of the output polarizations are created by the polarizer.
One of these two images is chosen for speckle nulling.
The other image is simply recorded.
The goal is to predict the contrast in this un-nulled polarization, assuming the other polarization is nulled to its theoretical minimum.

Theoretical Contrast Plots for Polarization Orthogonal to the Polarization Being Nulled

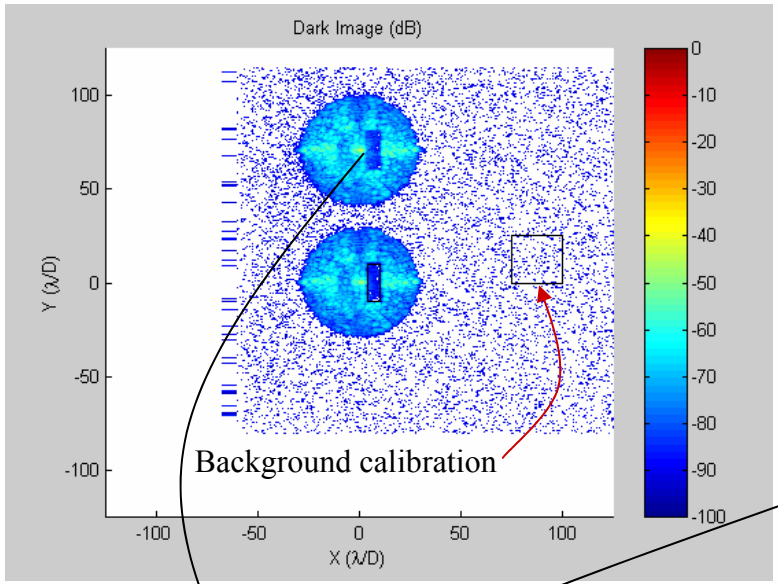


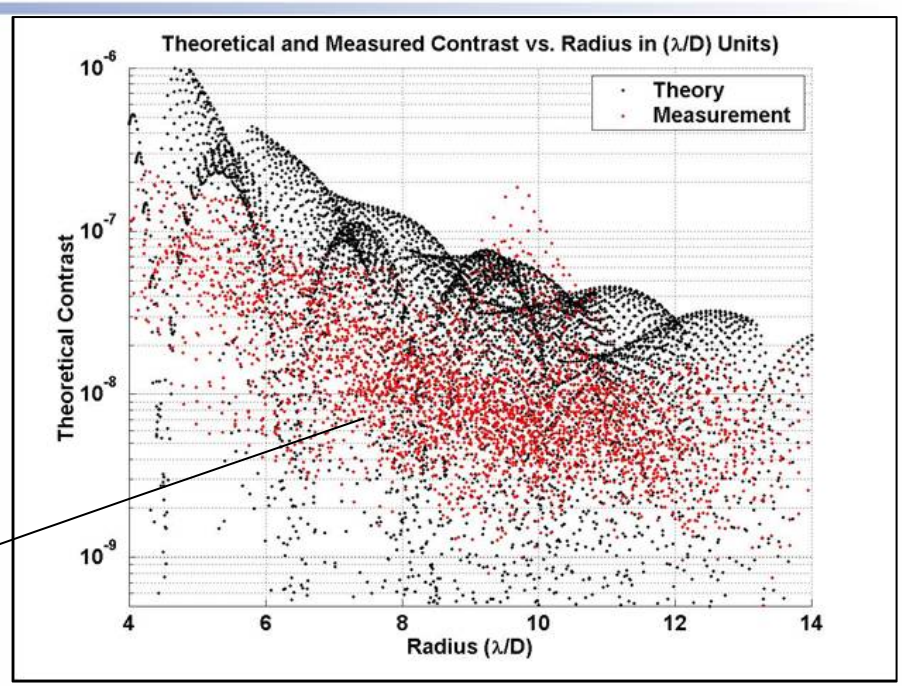


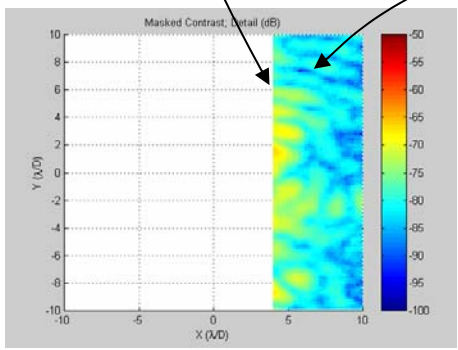




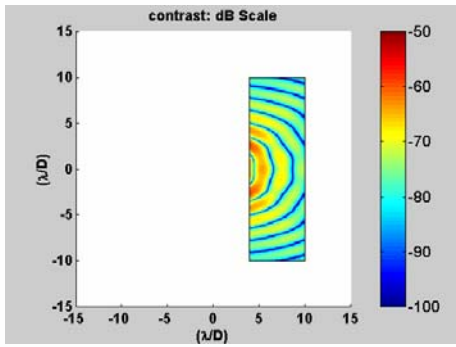
TPF Terrestrial Planet Finder







Expt, Red Data Points



Theory, Black Data Points

Polarization not nulled by DM settings

Contributing factors to observed differences between simulations and experiment:

1. Experiment was done at best focus offset; calculations are for zero defocus
2. In the model, the orthogonal polarization is perfectly nulled to zero, experimental nulling is at its best to a level of 4×10^{-9}
3. Approximations in the mask model: local (a) thick grating approximation for electromagnetic effects, (b) glass substrate not included (c) imperfect conductors not included

TPF Terrestrial Planet Finder

Summary

- Gray Scale and Binary focal plane masks for Lyot Coronagraph architecture have been designed, fabricated and tested at JPL
- Contrast in the range of 10^{-9} has been demonstrated over a nulled region comprising 4 to 10 Airy radii in the final image plane
- Future Work
  - Mask technology development towards broad band performance improvements
  - Test bed enhancements
  - Broadband measurements
  - Sensitivity analysis through models and experiments
  - 8th Order Masks
  - Other types of masks

References:
1) Kuchner, M. J. and D.N. Spergel, "Notch Filter Masks: Practical Image Masks for Planet-Finding Coronagraphs", The Astrophysical Journal, 594:617-626, 2003.
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3) Trauger et al., Coronagraph contrast demonstrations with the High Contrast Imaging Testbed, Proc. SPIE 5487, (2004), pp. 1330-1336
4) Wilson et al., Eclipse apodization: realization of occulting spots and Lyot masks, Proc. SPIE 4860, (2003), pp. 361-370.
5) Halverson et al, Measurement of phase and optical density of TPF coronagraph occulting mask materials, Proc SPIE Vol 5905 (2005)
6) Canyon Materials, Inc. San Diego CA, http://canyonmaterials.com

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