K. Lyon 02 Requirements AST 120.11

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Terrestrial Planet Finder Mission

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TPF Minimum Mission Requirements and Mission Overview

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Mission

Overview

- Science Requirements
  - Detection of terrestrial planets
  - Spectroscopy of terrestrial planets
- Important Definitions
  - Fundamental instrument and astronomical terms
- Derived Requirements based on Design Reference Mission Model
  - Instrument specifications and performance
  - Integration time per source
  - Mission strategy: visits per source, total number of sources
- Observational Strategy
  - Rolls
  - Dithers
  - Planet signal extraction

Science Requirements 1

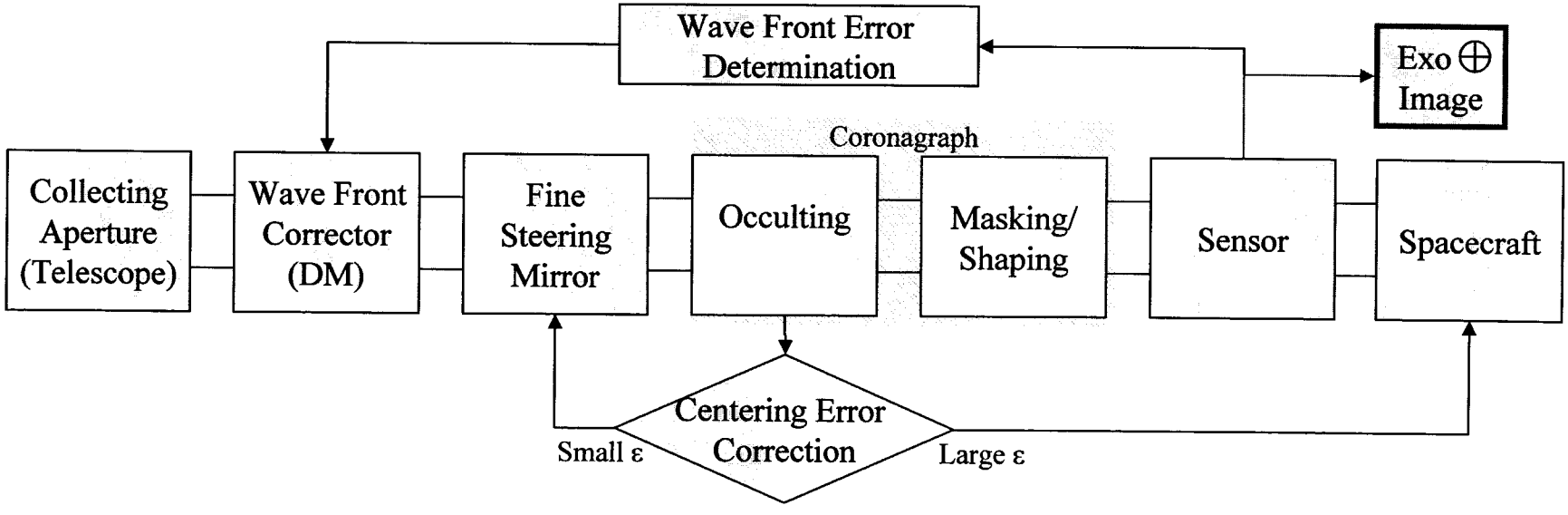
- Detection of terrestrial planets in the Habitable Zone (HZ)
  - The HZ is defined to be the region where liquid water exists, from 0.7 – 1.5 AU for a solar type star. The distance scales with luminosity.
  - Planets: terrestrial planets have area >= 0.5 earth area and similar albedo.
  - Minimum number of targets: 35
  - Type of targets: Nearby stars of spectral type F,G, and K
  - Completeness: 90% for each of 35 sources
    - Science Working Group has stated that completeness can be traded for more sources.
  - Bandpass: 0.5 – 0.8 microns, with operation to 1.05 microns desirable
  - Length of program: 3 years

Science Requirements 2

- Spectroscopy/Color
  - Determine equivalent width to 20% accuracy of spectral features of O2, H2O, O3, with spectral resolution of 70.
  - Measure flux ratio in 3 broad wavelength bands to 10% accuracy.
  - Must be able to spectrally/color characterize 50% of detectable planets.
- OUR DESIGN WORK TO DATE IS FOCUSED ON DETECTION.
  - Error budget and optical model assume detection requirements.
  - Spectral requirements drive system to very long integrations
    - Stability should be superior to detection scenario.

Definition: Stellar Coronagraph

- Stellar coronagraph
  - An instrument that suppresses diffracted light from a star, allowing detection of a faint object in close proximity to the star.
  - To be effective, the coronagraph requires a deformable mirror for controlling low-and-mid spatial frequency scattered light.



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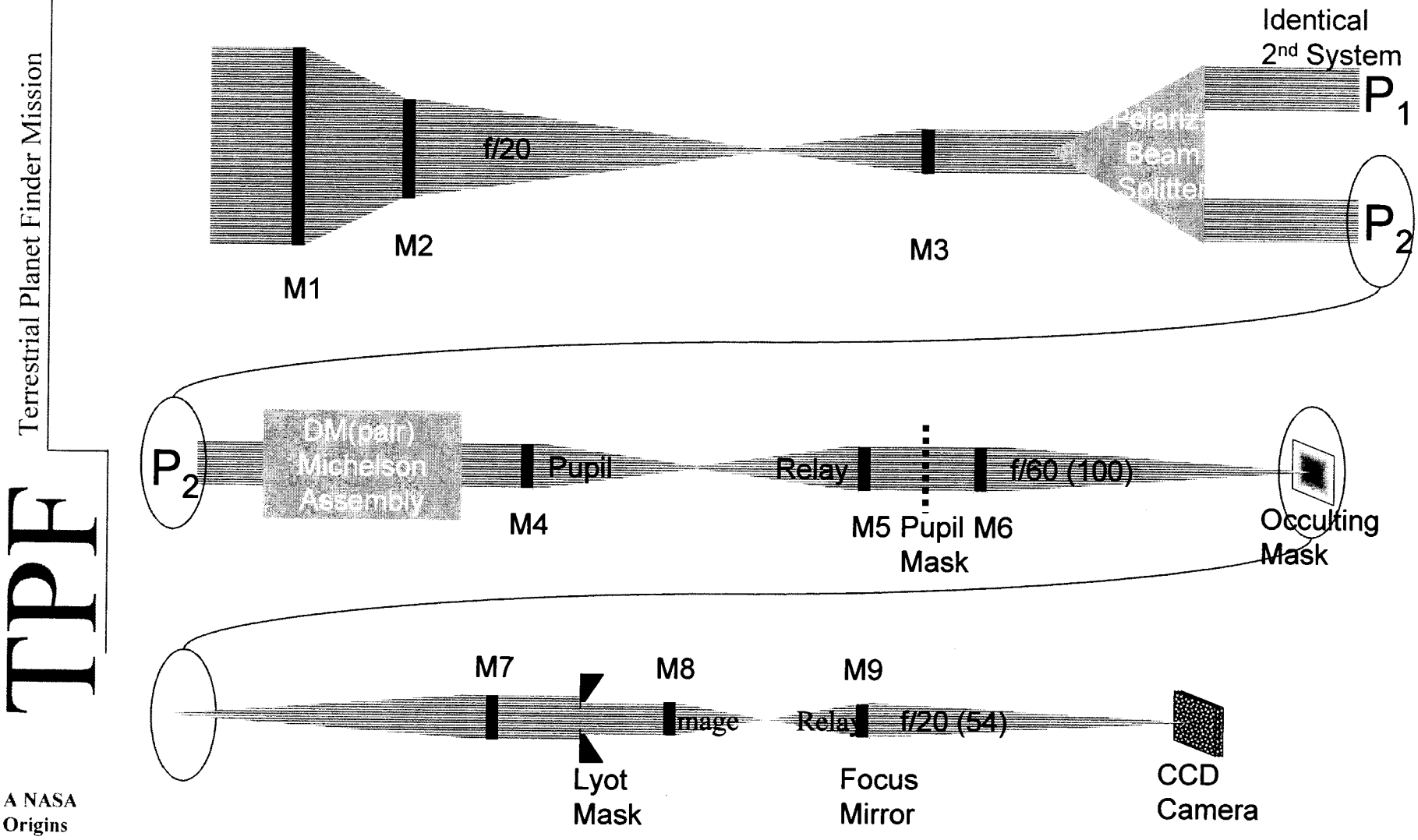
TPF Optical Schematic



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Definitions: Image Plane Terms

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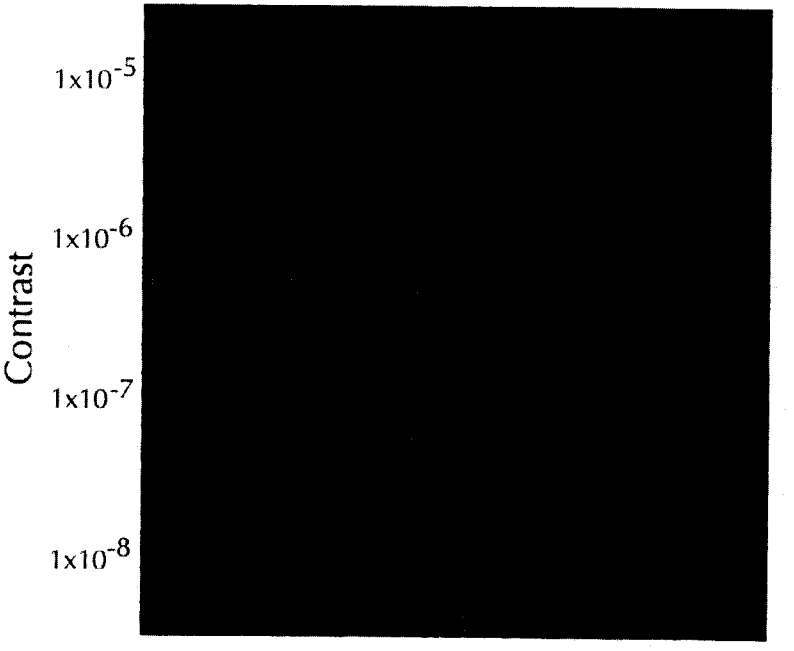
- Contrast: At any point in the image plane, the *contrast* is the ratio of the scattered light from a star centered on the coronagraph to the theoretical light level if the star were centered at that point.
- Dark Hole: The dark hole is the region around the center of the image plane where diffraction and stray light are controlled.
- Inner and Outer Working Angles: the inner and outer edge of the dark hole, expressed as an angle.
  - The inner edge is typically a few lambda/D (few Airy rings).
  - The outer edge is limited by the number of Deformable Mirror (DM) elements.
    - Maximum spatial frequency controlled is N/2.
    - N for flight is ~100. N=42 is already demonstrated in the lab.



Linear $sinc^2 x$ occulter

Picture from TPF HCIT Testbed, by J. Trauger, Feb. '04

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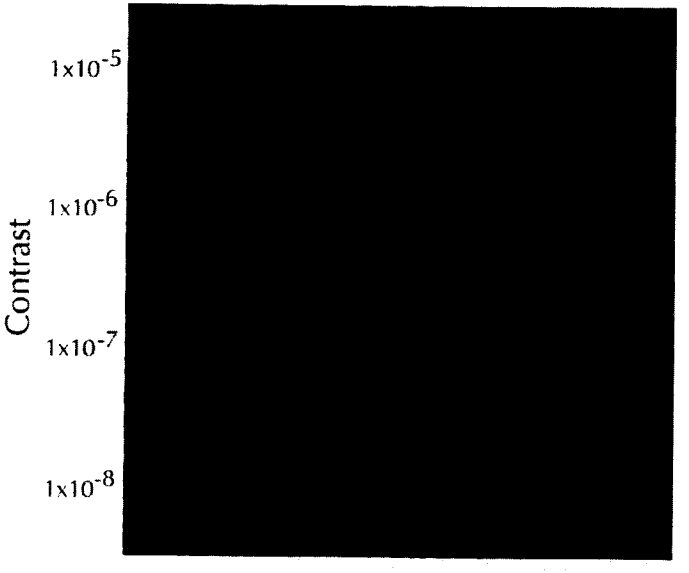
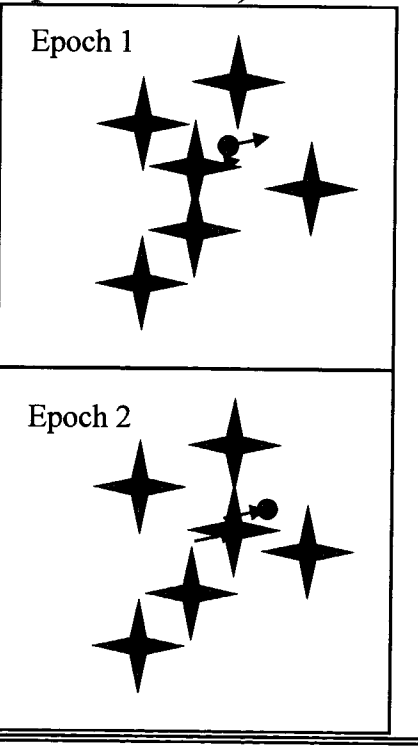
Definition: Detection

- Detection
  - A planet is *detected* when its signal is discriminated from noises sources with a Signal to Noise Ratio (SNR) = 4.
    - SNR = 4 is a self-imposed value. It is reasonable given the small number of targets and the requirement to confirm the detection.
  - The detection is *confirmed* when the planet is detected at a later epoch and shown to be associated with its parent star (via common proper motion).





Definition: Detection Completeness

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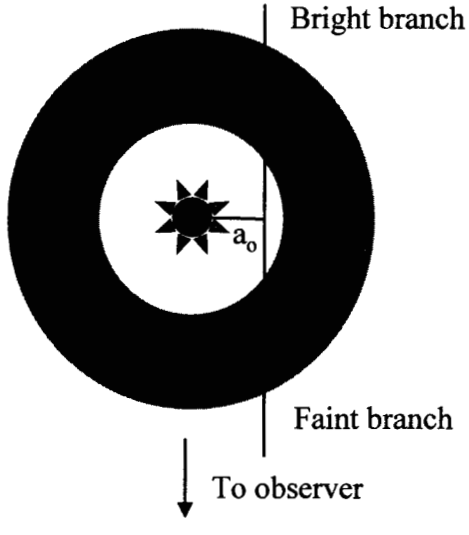
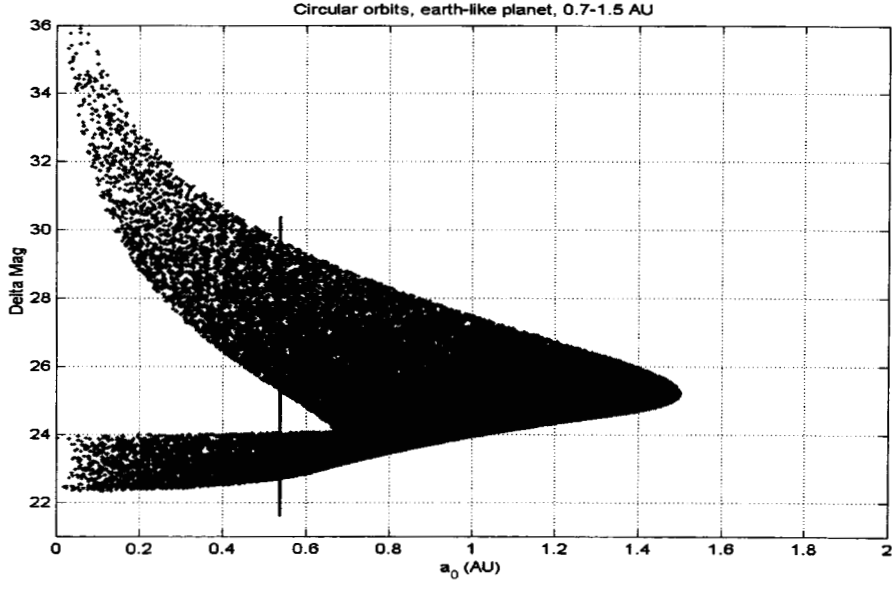
- Completeness: the cumulative fraction of possible planets found (Definition from Dr. R. Brown of STScI).
  - There are many types of completeness, e.g. visit completeness, program completeness. We generally refer to the program completeness, associated with the full program of observations over the course of the mission.
- Completeness is governed by:
  - The Inner Working Angle: planets can not be detected in orbits that are smaller than the IWA.
  - The limiting instrument delta magnitude: planets are not detected if they are too small, too distant, or at unfavorable phase angles relative to their parent star.
- Trade:
  - Obviously we desire a small IWA and deep delta magnitude.
  - Smaller IWA requires large apertures (and/or shorter wavelengths).
  - Deeper delta magnitude requires lower scattered light and more stable optical train, as well as longer integration times (leading to fewer sources studied during 3 years).

Definition: Delta Magnitude

- Astronomers use the magnitude scale to describe the brightness of stars.
  - Brightest star is ~ V ~ -1
  - Faintest to naked eye is V~6
  - Every 5 magnitudes is a factor of 100 in brightness.
- An earth-like planet in a face-on orbit at 1 AU around a solar-type star is 24.34 magnitudes fainter than the star (a factor of 1.8e-10).

$$\Delta m = 2.5 \log_{10}(I_1 / I_2)$$





Design Reference Mission Model

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- Purpose: determine the number of planets detectable and completeness per star for a list of nearby stars.
  - Study different architectures, e.g. 6x3.5 ellipse, segmented aperture, etc.
  - Study sensitivity to IWA, delta magnitude, throughput, bandpass, etc.
- Parameters
  - Solar system zodiacal light, exo-zodiacal light
  - Instrument background
  - Various coronagraph masks with appropriate image-plane sampling completeness and throughput
- Key Assumptions
  - Perfect subtraction of static speckles (to shot noise limit)
  - All noise is shot noise from background light, image plane speckles, and source.
  - Source list is from D. Ebbets (Ball Aerospace). List was created for the Ball TPF mission study NRA. It includes most of the nearby F, G, and K stars (259 stars).
  - 3 year program.
  - The model computes integration time. It does not compute overhead.
    - ALLOCATION: 1 YEAR FOR INTEGRATION TIME, 2 YEARS FOR OVERHEAD.
  - 90 degree solar avoidance angle.

Derived Performance Requirements For a Viable TPF Mission

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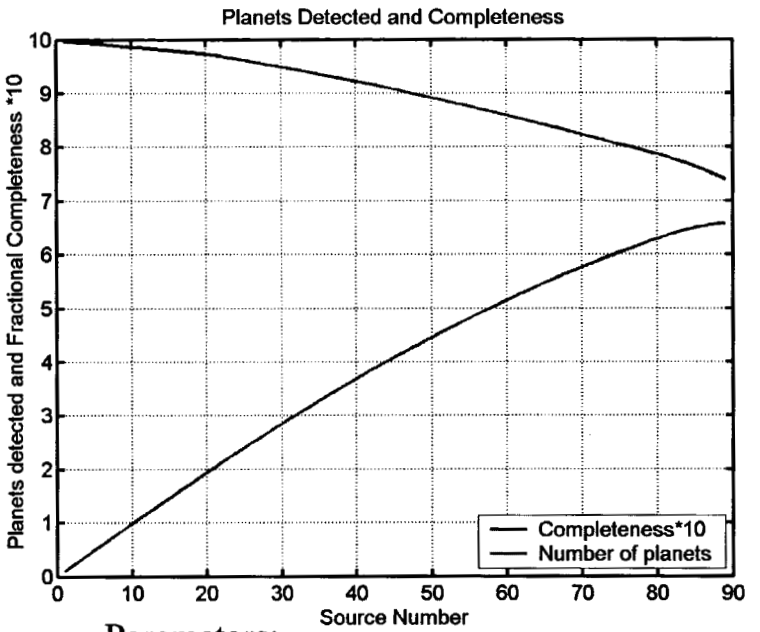
- Detect planets with delta magnitude = 26 (4e-11 of star) with and SNR = 4.
  - Requires instrument contrast stability of 1e-11.
  - Integration times range from 1e2 – 1e5 s.
- Achieve a static contrast of 1e-10.
  - Thus the faintest planets detected will appear at a level of 0.1 of the speckles.
- Utilize an Inner Working Angle no larger than 62 milli-arcsec.
  - Corresponds to a 6 m aperture, wavelength = 600 nm, working at 3 lambda/D
  - Likewise, an 8 m aperture at 4 lambda/D achieves the same resolution.
- Make observations at 2 orthogonal positions about the line-of-sight (Rolls)
  - Required to achieve adequate completeness at inner working angle
- Utilize a bandpass of 100 nm.
  - Required to keep integration times low. Wider bandpass pushes out IWA.



Parameters:
-Aperture 6x3.5 m
-IWA = 3 lambda/D
-Bandpass 0.5 – 0.6 microns
-Elliptical-shape coronagraph mask
-2 rolls about Line of Sight
-4 visits over 3 years
-1 earth area
-Delta mag = 26
-Exo-zodi = 1 earth zodi
-Coro thruput = 0.45
-Instrument delta mag = 25

Observational Strategy

- Visits/Scheduling
  - Four visits per target over 3 years
  - With ~ 50 targets, that's 200 visits over 1000 days, or 5 days/visit
  - Two of the visits should be within 6 months of each other due to 90 deg solar avoidance constraint.
- Rolls
  - Used to improve completeness.
  - Each visit includes observation at two orthogonal roll positions.
    - e.g. Observe at orientation theta, then roll about LOS to theta+90.
  - Large roll angle induces significant distortion of optics and structure.
- Dithers
  - Speckles are at 1e-10 and need to be subtracted to 1e-11. We believe we can do this by making a small roll about the LOS, re-observing, then subtracting the (hopefully) fixed background.
  - Each roll position is split into two minor-roll positions, called dithers.
    - E.g. Observe at theta+10, theta-10, theta+100, theta+80.
- Diagram on next page.

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Completeness at IWA for an Elliptical Aperture

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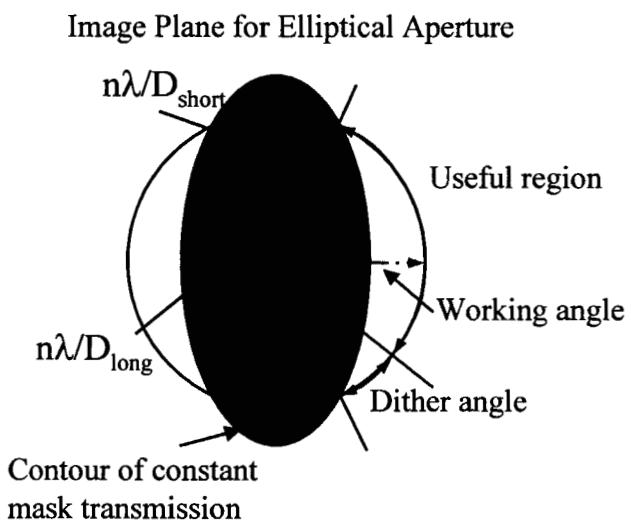
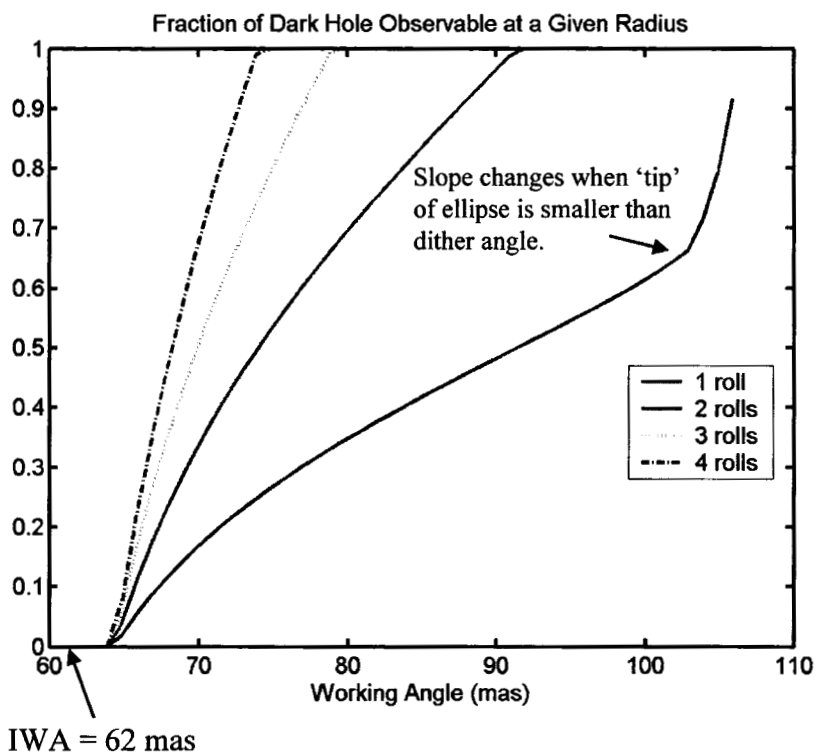
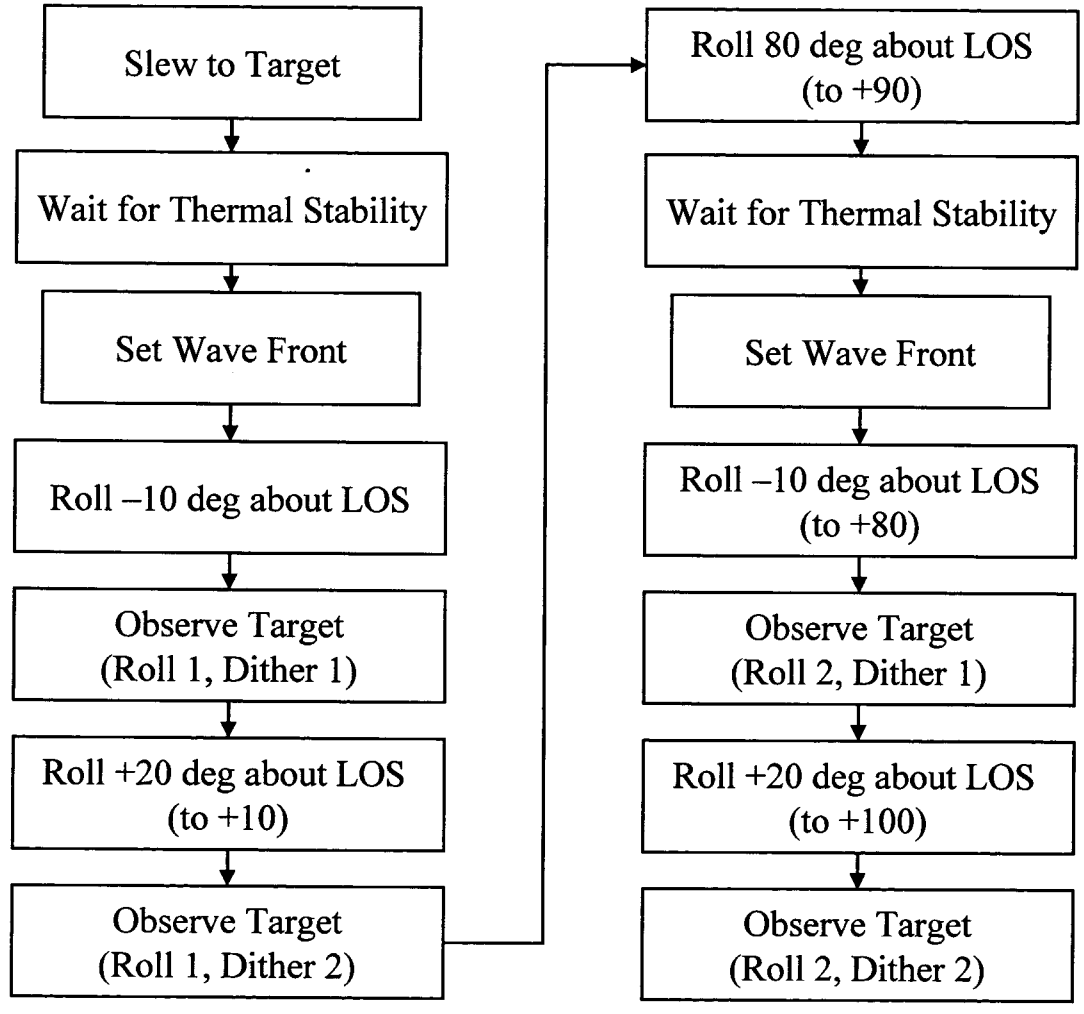
Aperture is 6 x 3.5 m ellipse, working at 3 lambda/D, lambda = 600 nm.





Observation Strategy



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Planet Signal

- The observable signal is: Dither 1 – Dither 2 for each roll position.
  - Dither 1 – Dither 2 subtracts the fixed-pattern noise, leaving only stochastic noise and two planet images separated by the dither angle.
  - The planet signal is pulled out using a matched-filter approach.
  - Roll angles >= 20 degrees are required because the planet may be at 3 lambda/D
    - Width = lambda/D
    - Position = 3 lambda/D
    - Angle = 0.33 radian ~ 20 deg.
- Roll 1 + Roll 2 gives adequate sampling near IWA.
  - Single roll only samples near IWA along long-axis of telescope.

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Summary

- Visit each target 4 times over 3 years.
- Each visit has two orthogonal rolls about LOS.
  - Each roll has two 'dither' positions separated by 20 deg roll about LOS.
- Each visit requires ~ 100 – 1e5 s of integration.
- If necessary, TPF can spend a few days per target to cover 50 targets.
- The instrument achieves contrast of 1e-10, contrast stability of 1e-11.
- We have chosen as our point design a 6x3.5 m off-axis telescope with a monolithic primary mirror. The coronagraph achieves IWA = 3 lambda/D (62 mas).

Backup Slides Follow

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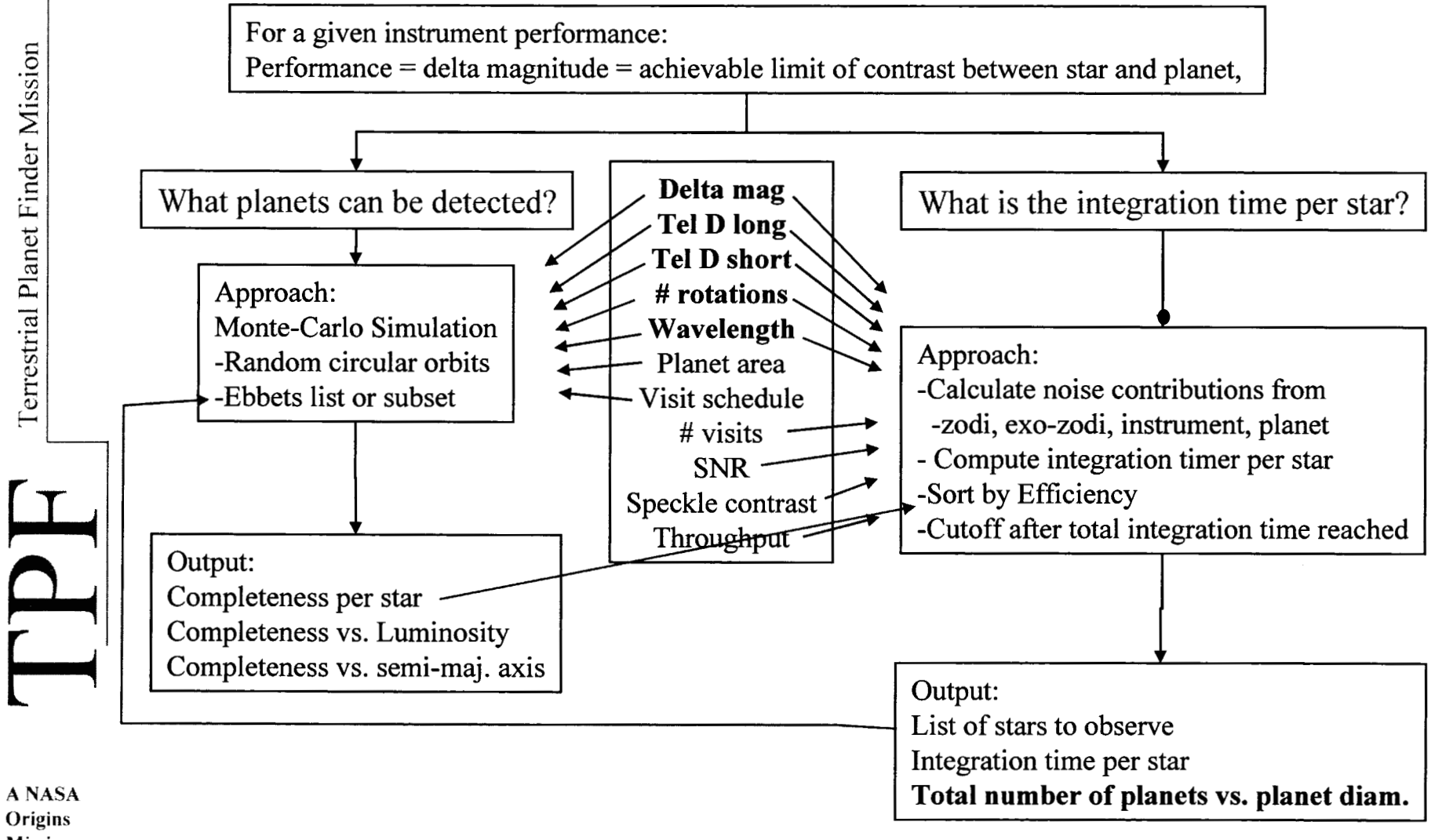
Design Reference Mission Study Tools



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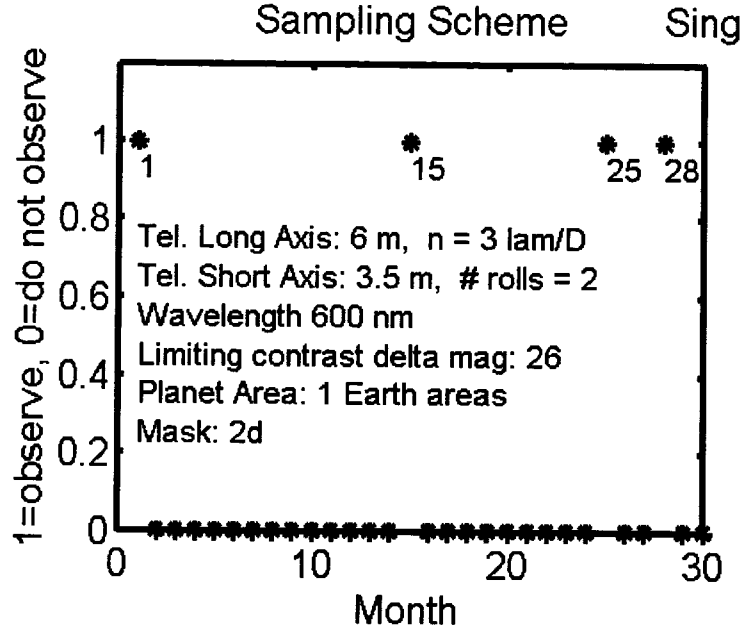
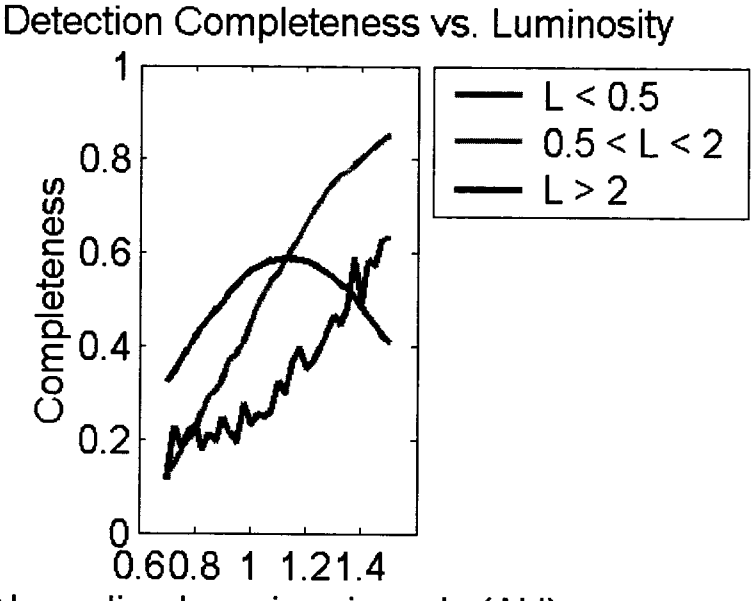
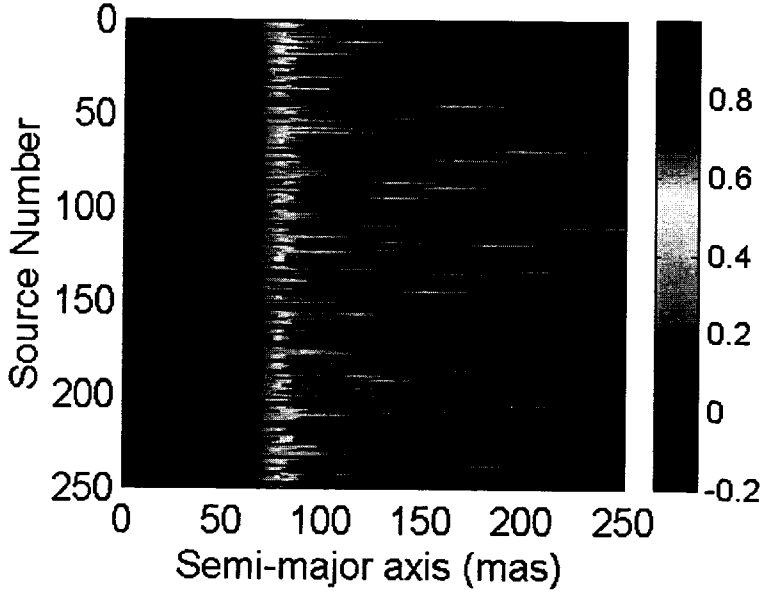
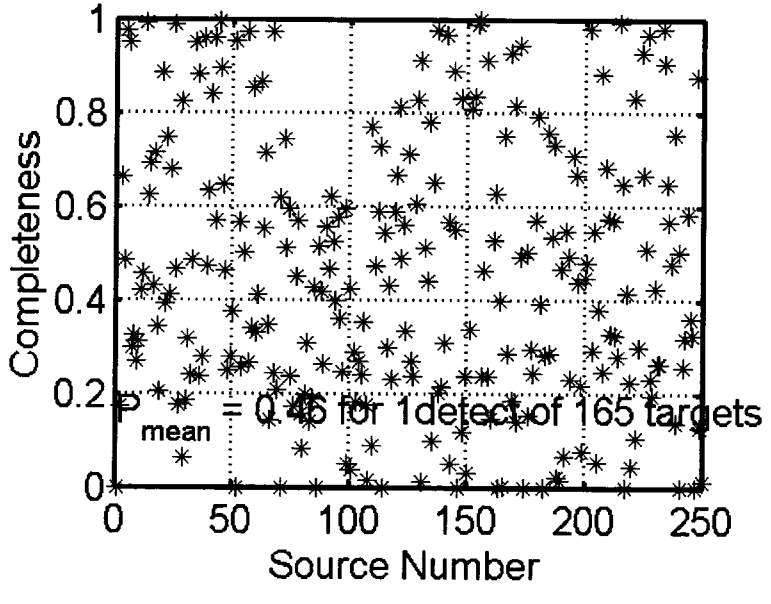

Sampling Scheme
1=observe, 0=do not observe
1
15
25
28
Tel. Long Axis: 6 m, n = 3 lam/D
Tel. Short Axis: 3.5 m, # rolls = 2
Wavelength 600 nm
Limiting contrast delta mag: 26
Planet Area: 1 Earth areas
Mask: 2d
Month


Single Detection Completeness vs. Luminosity
L < 0.5
0.5 < L < 2
L > 2
Completeness
Normalized semi-major axis (AU)


Program Obscur. and Phot. Completeness
Source Number
Semi-major axis (mas)


Program Obscur. and Phot. Completeness
Completeness
P mean = 0.46 for 1detect of 165 targets
Source Number