



Exoplanet Yield Modeling for ExEP

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May 2, 2016

Decadal Concept Studies



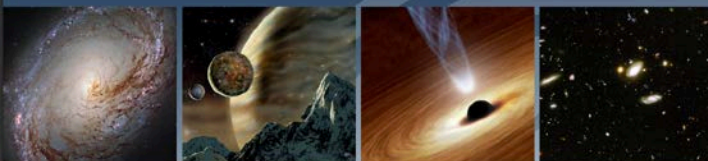
ExoPlanet Exploration Program



National Aeronautics and Space Administration



Astrophysics



Large Mission Concept Studies Kick Off
AAS 227th Meeting
Kissimmee, Florida
January 6, 2016

Paul Hertz
Director, Astrophysics Division
Science Mission Directorate
@PHertzNASA

Guiding documents for the mission concept studies are posted at
<http://science.nasa.gov/astrophysics/2020-decadal-survey-planning/>

Large Mission Concept Studies



NASA will initiate mission concept studies of the following four large mission concepts:

- **FAR IR Surveyor** – The Astrophysics Visionary Roadmap identifies a Far IR Surveyor as contributing through improvements in sensitivity, spectroscopy, and angular resolution.
- **Habitable-Exoplanet Imaging Mission** – The 2010 Decadal Survey recommends that a habitable-exoplanet imaging mission be studied in time for consideration by the 2020 Decadal Survey.
- **Large UV/Optical/IR Surveyor** – The Astrophysics Visionary Roadmap identifies a Large UV/Optical/IR Surveyor as contributing through improvements in sensitivity, spectroscopy, high contrast imaging, astrometry, angular resolution and/or wavelength coverage. The 2010 Decadal Survey recommends that NASA prepare for a UV mission to be considered by the 2020 Decadal Survey.
- **X-ray Surveyor** – The Astrophysics Visionary Roadmap identifies an X-ray Surveyor as contributing through improvements in sensitivity, spectroscopy, and angular resolution.



Exoplanet Probe Studies

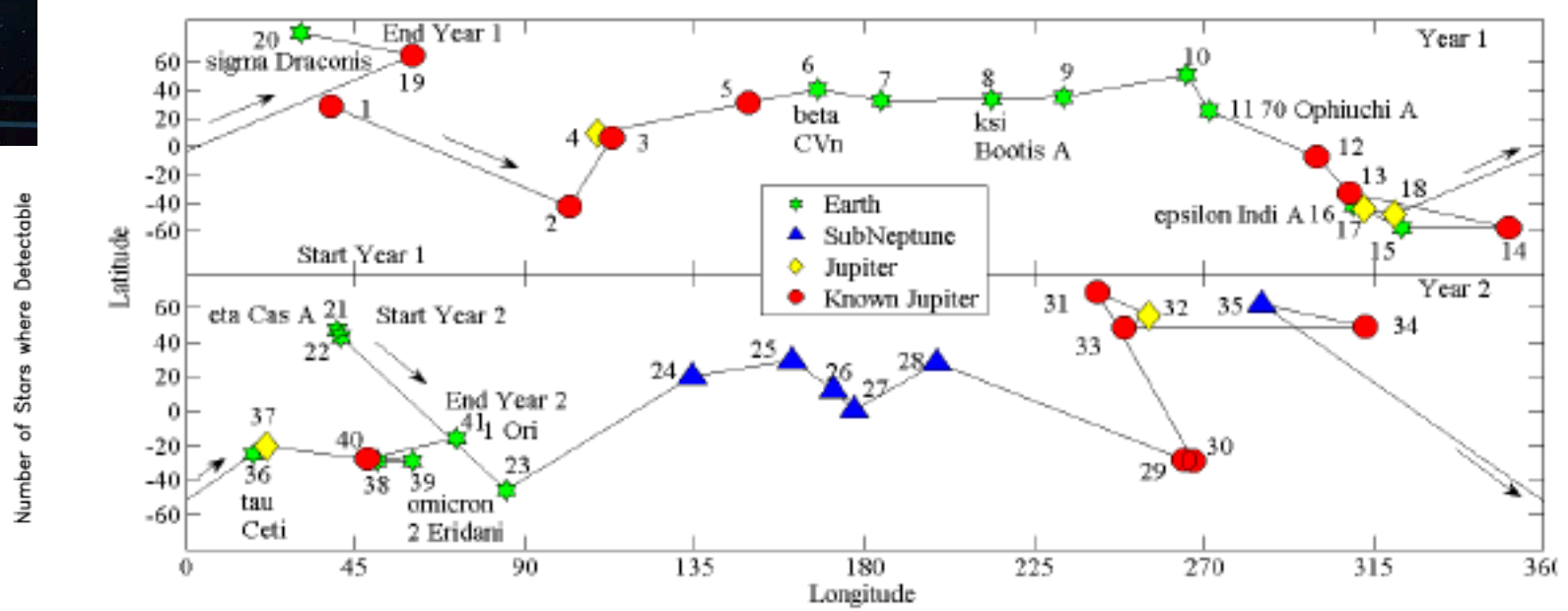
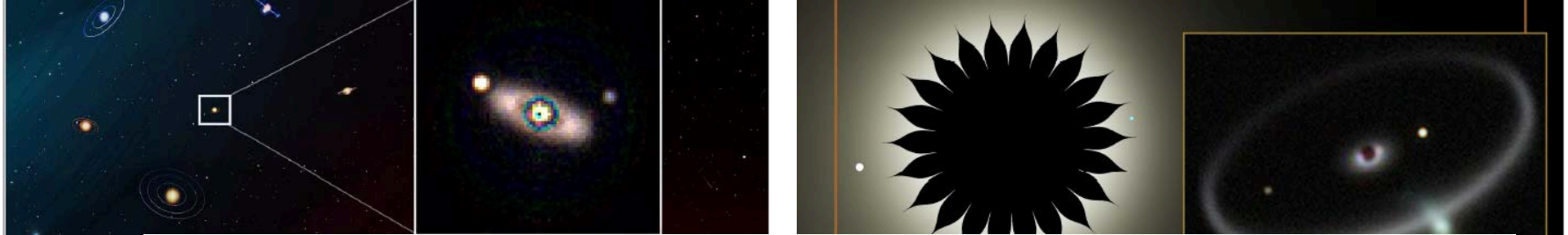
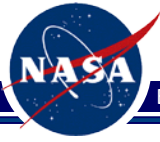


Figure 5.3-1. Observing sequence for Case 1, Dedicated Mission, Earth twins in HZ. Coordinates are ecliptic longitude and latitude. Stars, as a function of planet size and orbit.

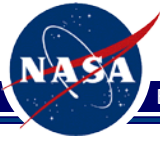


Yield Estimation for Decadal Studies



- The Decadal concept studies include two studies featuring exoplanet science. In light of this, the Exoplanet Exploration Program Office commissioned the development of a yield model to be the **standard measure** of performance for work within the Exoplanet Program
 - The yield model will be **open source and distributable** for use by the community
- ExEP is chartering a Standards Definition and Evaluation Team to provide **transparent, common** exoplanet science yield estimates for Decadal missions and probes.
 - Standards team promotes **standard and consistent** definition of inputs and outputs for purposes of yield comparison

ExEP Yield Tool Charter



ExoPlanet Exploration Program



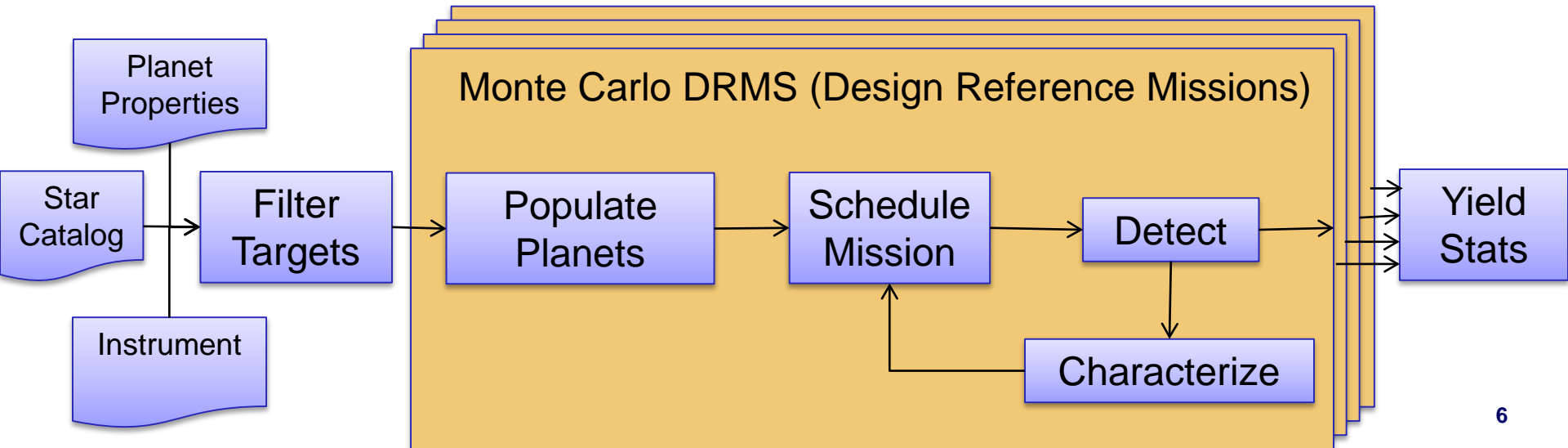
- **Objective**: build a tool capable of the **consistent comparison** of the science performance of the full range of expected exoplanet mission concepts for the next Decadal Survey
- **Missions supported**: segmented telescopes with coronagraphs; monolithic primary mirror telescopes with coronagraphs; different coronagraph designs; starshade missions
- **Features**: Completeness calculator, planet detection yield calculator, characterization yield (orbital characterization, atmospheric properties), Design Reference Mission (DRM) schedule optimization
- **Transparent about**: Planet physical properties and occurrence rates (utilize SAG13 findings); Model assumptions; Science Figures of Merit; **Validation and cross validation**



Science Yield Model Code Features



- Full physics-based diffraction models of coronagraph or star-shade performance
 - John Krist runs PROPER diffraction simulations for coronagraphs
 - Eric Cady runs boundary diffraction wave calculation for star shade petals
- Realistic spacecraft and mission observing constraints
- Utilizes the EXOSIMS framework by Savransky under development for WFIRST
 - Contributions by Christian Delacroix, Daniel Garrett, Patrick Lowrance, Xiang Cate Liu, Rhonda Morgan, Michael Turmon
 - Python, open source: github.com/dsavransky/EXOSIMS
 - Object Oriented base class definitions allow for customization of modules
 - Can update model fidelity without impacting backbone
 - All parameters and modules specified via a single JSON-format text file
 - Pointers to files of star catalog and contrast data





Input Parameters



• Astrophysics

- Star list: EXOCAT1 or KnownRVplanets
- Planet Properties
- Exozodi brightness
- Background Sources

• Post-processing

- Contrast Factor

• Telescope

- D_aperture, Fill
- Throughput(angle)
- Contrast(λ ,angle)
 - PSF
 - IWA
 - OWA
 - Jitter/WFE
- Polarization
- Focal Plane
 - Pixel size
 - Detector noise
 - Dark rate
- Bandpass
- Spectral resolution
- IFS sampling

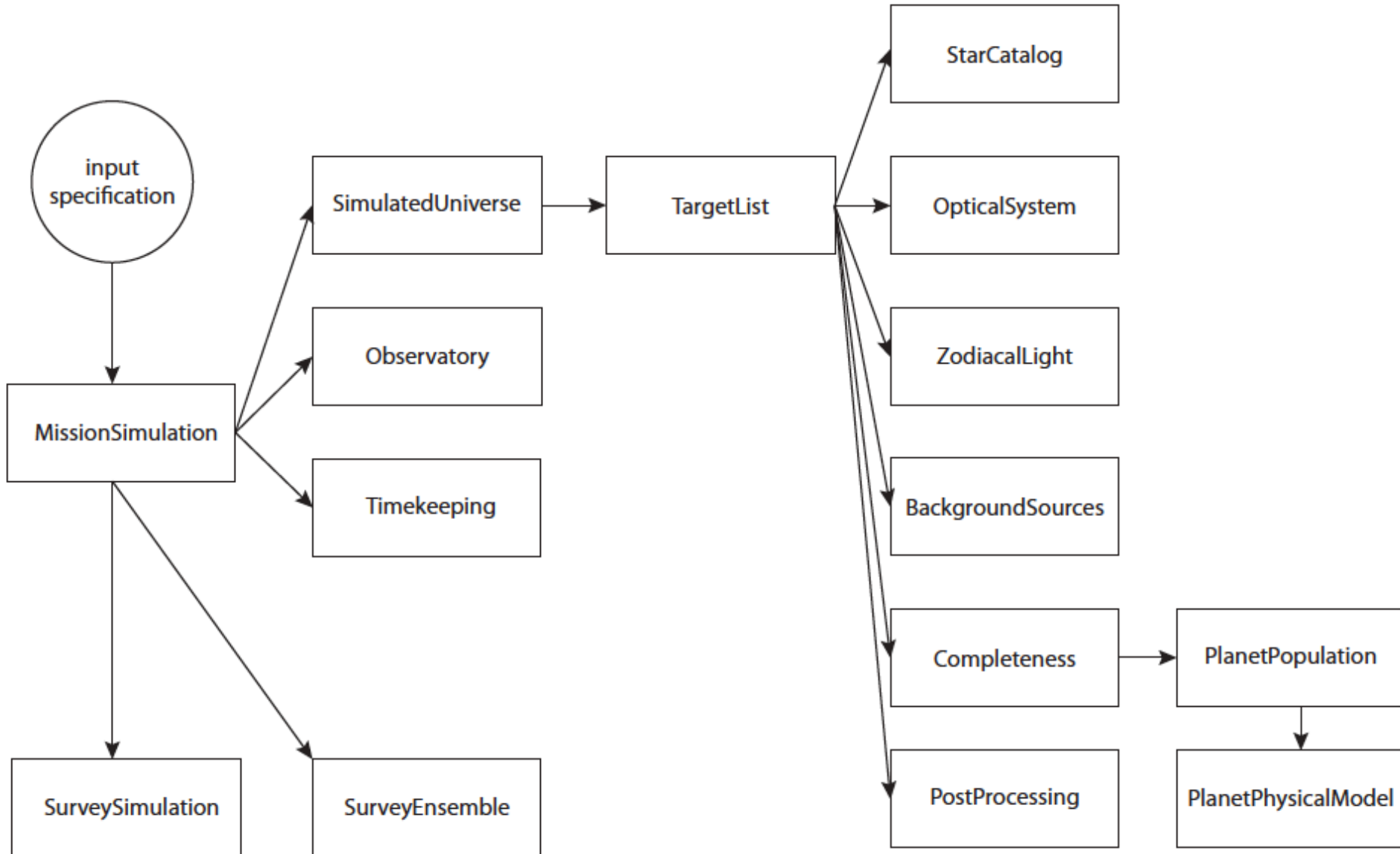
• Mission Design

- Mission duration
- Overhead
- Sun angle constraint
- Starshade propulsion
 - deltaV, fuel capacity, Isp
- Scheduling
 - Revisit schema
 - Target priorities
 - Detection Response

EXOSIMS Architecture



ExoPlanet Exploration Program





Code Validation is Important

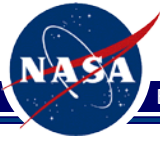


1. Unit Tests

1. Each method (sub-function) of each module is tested
 - Often this involves instantiation of the entire simulation object
 - Point-checks against test cases verify module results
2. Xx bugs identified and fixed
3. Critical Path unit tests are 45% complete. *Complete 5/31/16*

2. System Level Cross Validation

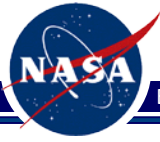
1. Wes Traub's comparison of Exo-S, Exo-C, WFIRST Coronagraph, WFIRST Starshade *Complete 6/20/16*
2. Chris Stark's AYO and Other codes using standard inputs (ExoCat starlist, SAG13 occurrences) for Decadal Mission Concept Studies



What is the Habitable Zone Problem Space in IWA and Contrast?

Rhonda Morgan

April 14, 2016



Let's meet our (potential) neighbors



- We know the stars within 30 pc that are potential targets
 - M. Turnbull's, "ExoCat-1: The Nearby Stellar Systems Catalog for Exoplanet Imaging Missions", arXiv:1510.01731, 2015
- We can define a Habitable Zone
 - Orbital radius of 0.7 to 1.5 AU
 - Eccentricity of 0 to 0.35
- We can select a planet radius
 - Earth radius (for now)
- We can treat planet properties as probability distributions and create a Monte Carlo cloud of probable planet locations around a star
- From each MC planet location, we can calculate the reflected light relative to the star (Δmag) and the apparent separation to the observer.

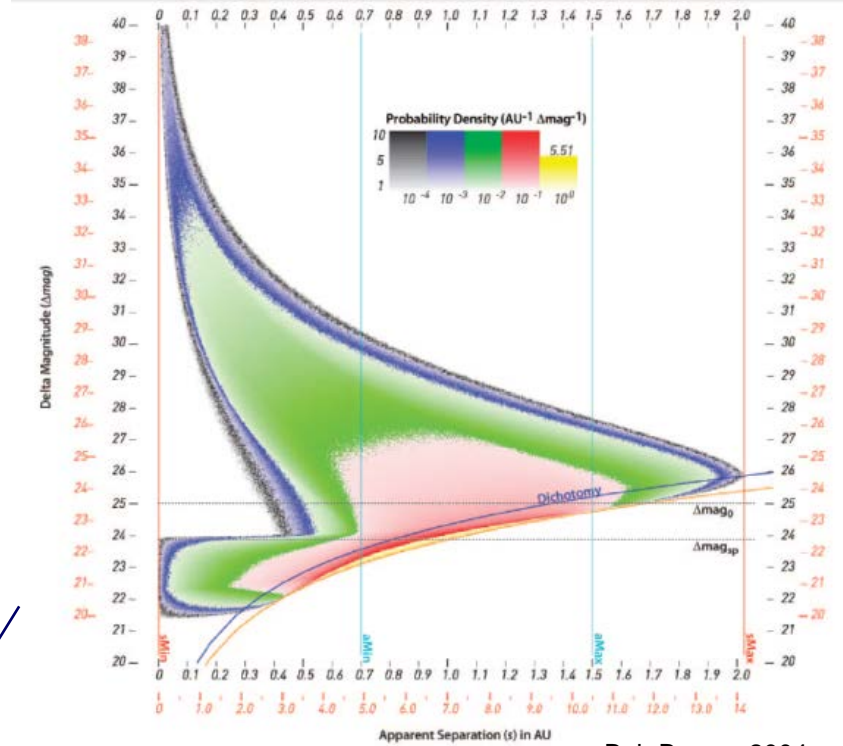


Brown MC Cloud of Planet Positions

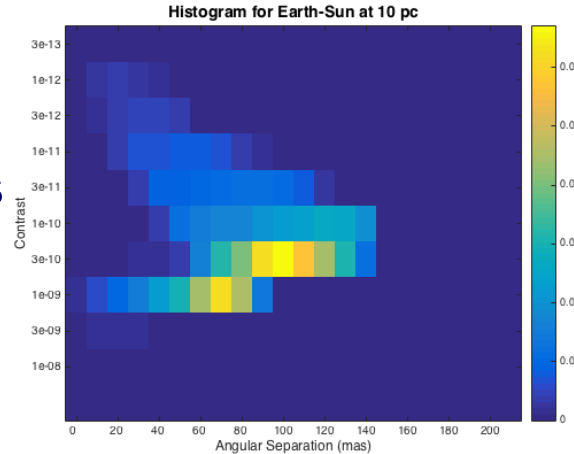


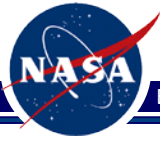
ExoPlanet Exploration Program

1. Simulate 10^5 planets using uniform random distributions:
 - Ecc = [0 .35]
 - HZ = [.7 1.5] AU
 - Inclination [0 180] deg.
 - R = Earth radius
2. For each star in ExoCat1
 - Scale angle
 - $s_j = s \cdot \sqrt{L_j} / \text{distance}_j$
 - Scale Δmag
 - $\Delta\text{mag}_j = \Delta\text{mag} + 2.5 \cdot \log_{10}(L_j)$
3. Histogram for each star in 2D
 1. Bin over problem space
4. Sum Histograms over all stars



Bob Brown, 2004

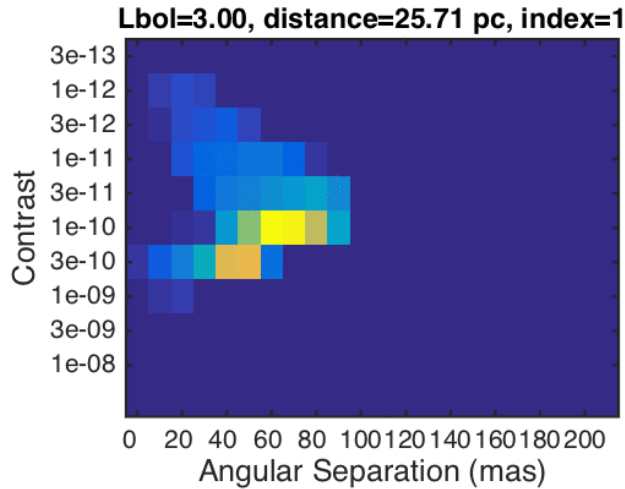




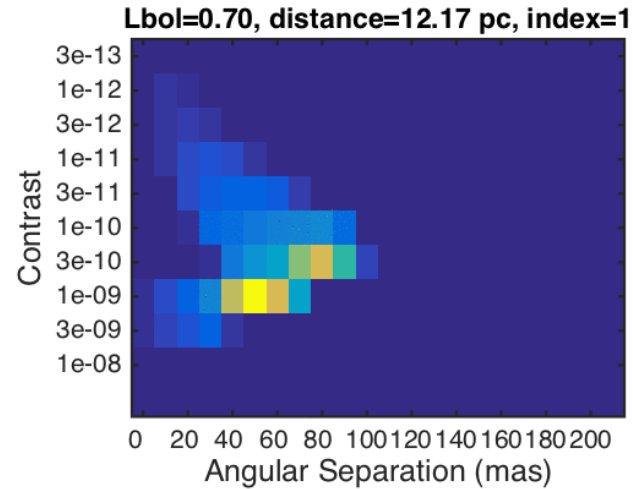
HZ Earth-Twin PDF for FGKM stars



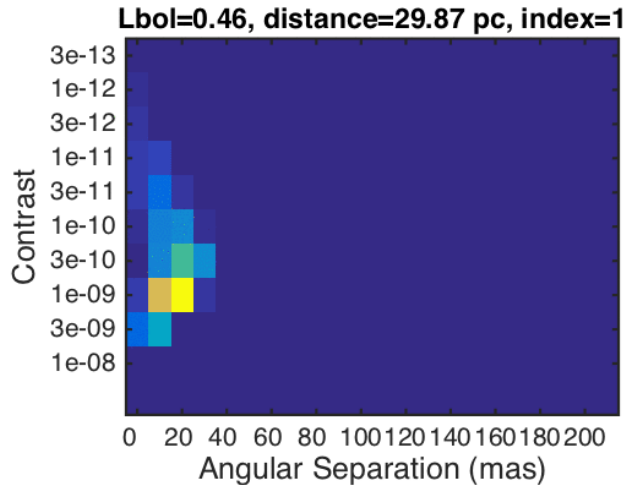
F



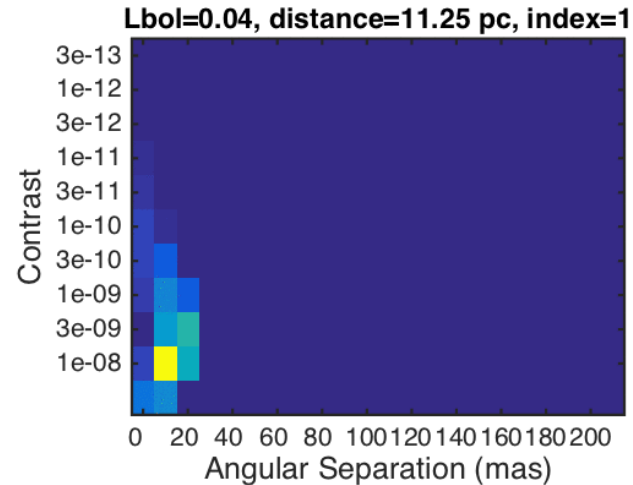
G

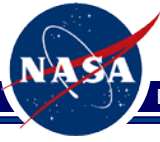


K



M

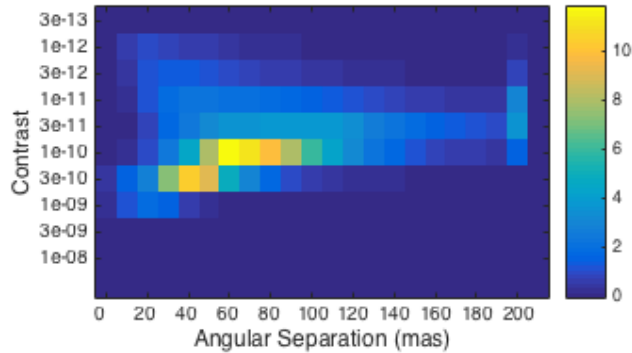




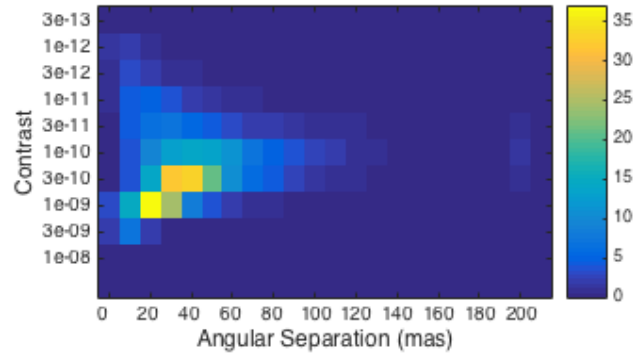
2D Probability Histograms Σ stars



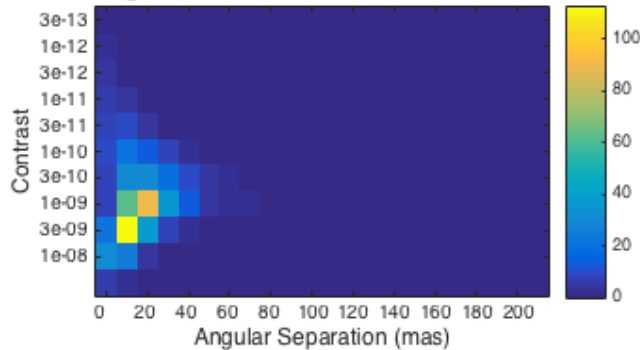
Histogram for F star HabZone Earth-twins



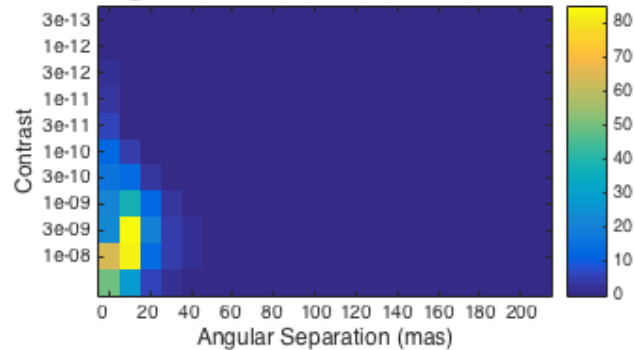
Histogram for G star HabZone Earth-twins

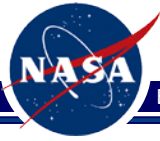


Histogram for K star HabZone Earth-twins



Histogram for M star HabZone Earth-twins

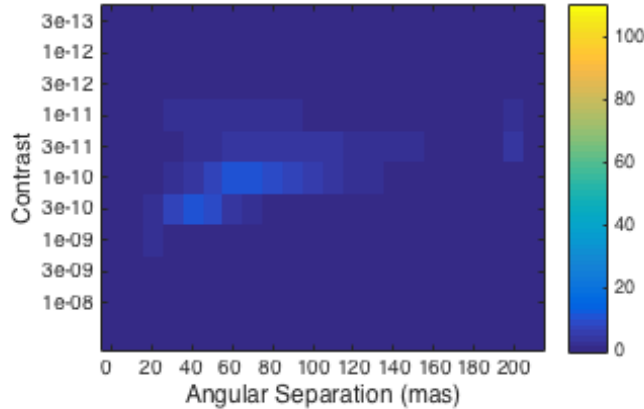




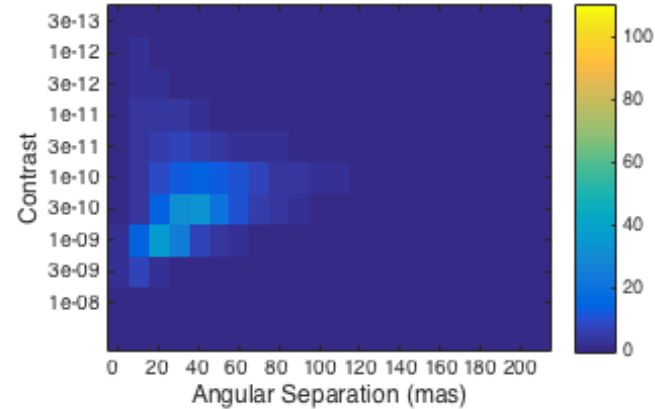
Same stretch on all star types



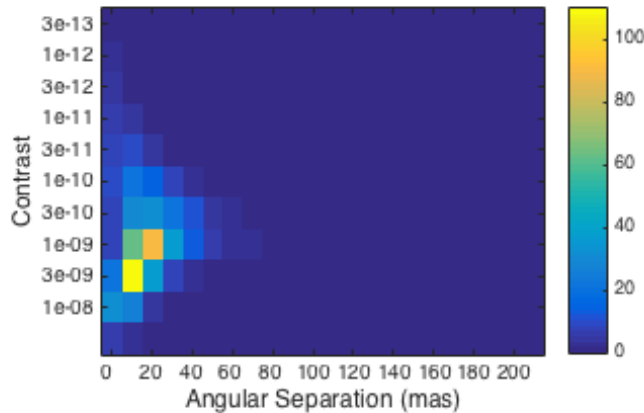
Histogram for F star HabZone Earth-twins



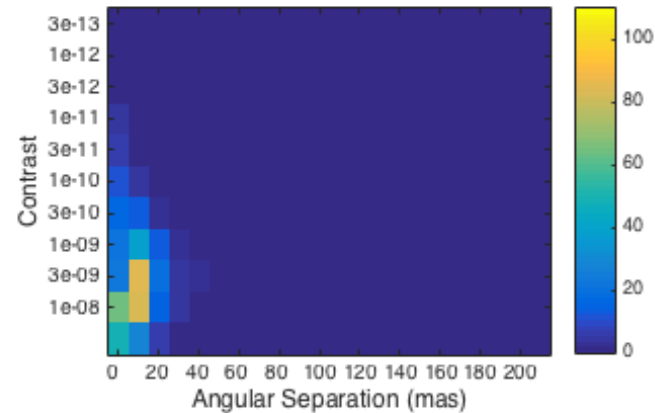
Histogram for G star HabZone Earth-twins



Histogram for K star HabZone Earth-twins



Histogram for M star HabZone Earth-twins





Completeness over IWA and Contrast



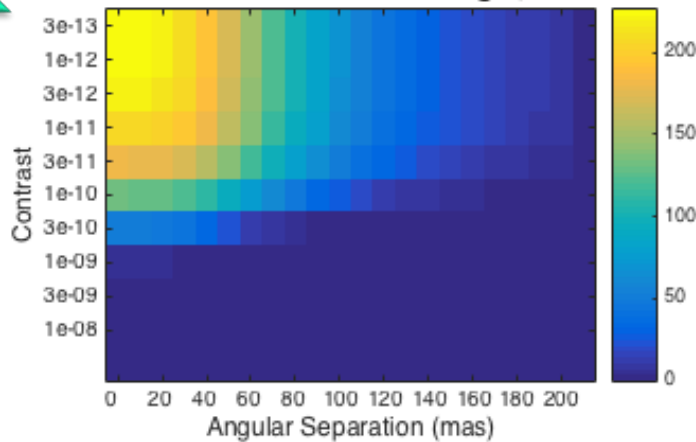
ExoPlanet Exploration Program

Completeness = η_{Earth} * plotted values

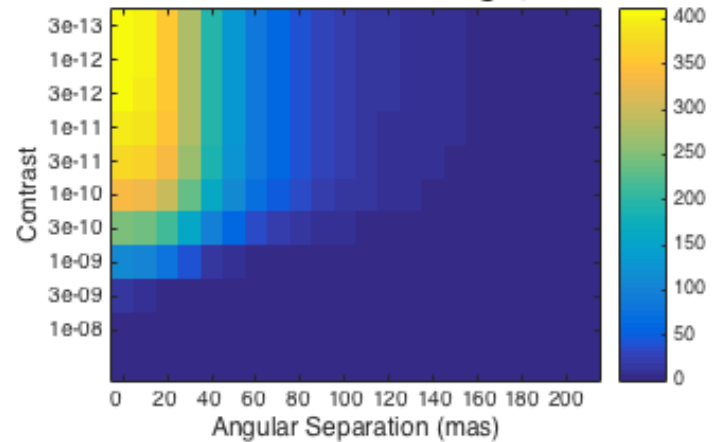
2. Integrate

1. Integrate

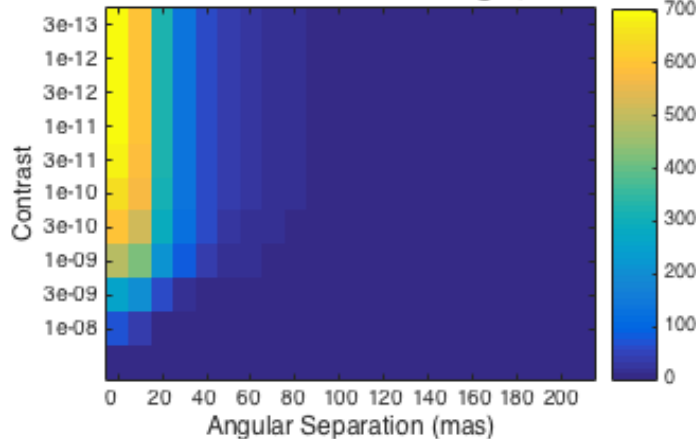
CumSum over contrast then angle, F star HZ



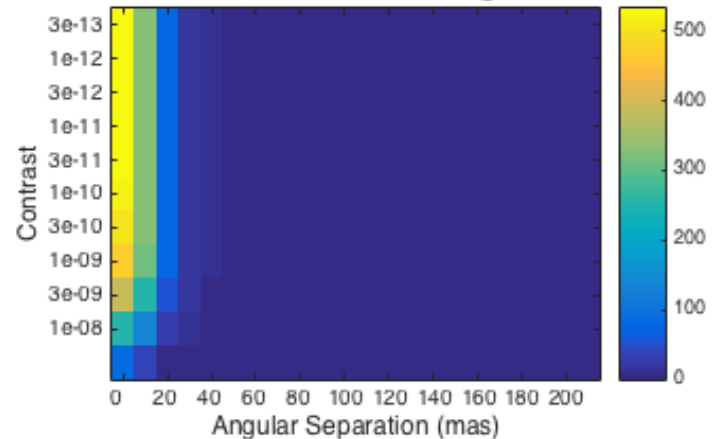
CumSum over contrast then angle, G star HZ



CumSum over contrast then angle, K star HZ



CumSum over contrast then angle, M star HZ





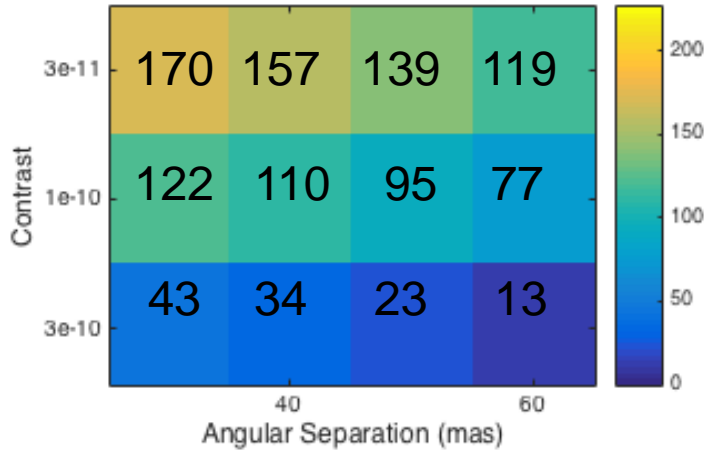
Completeness over IWA and Contrast



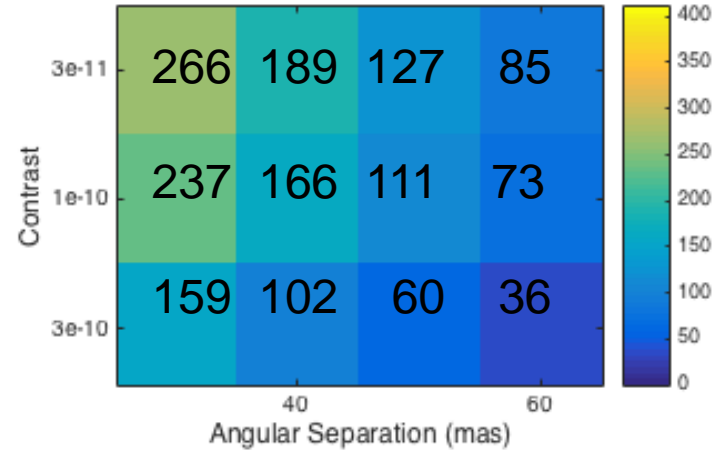
ExoPlanet Exploration Program

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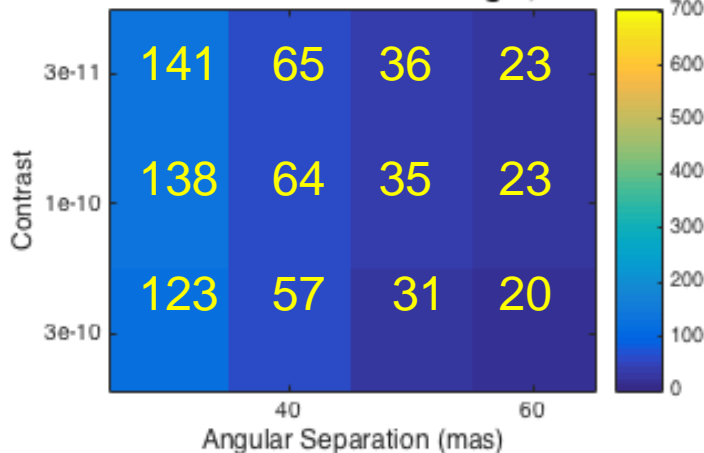
CumSum over contrast then angle, F star HZ



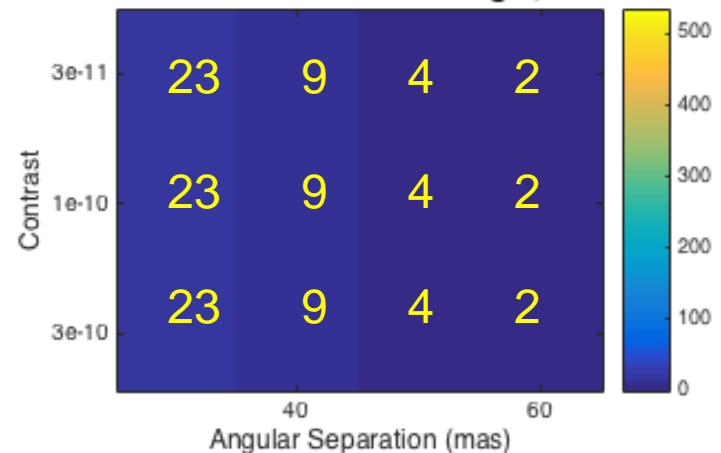
CumSum over contrast then angle, G star HZ

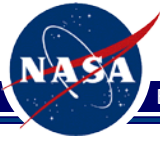


CumSum over contrast then angle, K star HZ



CumSum over contrast then angle, M star HZ





Notes



- This analysis is entirely independent of instrument
- These are not yield numbers. Yield involves detection which requires an instrument.



Future work



- Filter out binaries (<30 asec separation)
- Filter out below 30 mag (some detection threshold)
- Add revisits. Numbers will go up. Express the completeness for the observable HZ for infinite visits
- Add line of 2 lambda/d at 1 um for 10 m telescope (R=70 characterization)
- Add line of 2.5 lambda/d at 550 for 4 m
- Add line for 5 SNR detection 1e-11 detection