Results from the automated Design Reference Mission constructor for exoplanet imagers

SPIE Optical Engineering + Applications

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Motivation

- Multiple teams are currently developing direct detection planet-finding mission concepts.
- Multiple different instrument designs, mission scenarios and observing strategies have been proposed.
- We require an objective comparison of the capabilities and expected science yield of mission hardware and mission rules.
- We have created an analysis framework based on end-to-end mission simulations and applied it to several mission concepts.

Outline

Direct Detection Platforms

- Coronagraphs - multiple methods exist for removing light from the star entering a telescope's aperture.
- Occulters - a 'starshade' is flown along with the telescope to block out star-light.

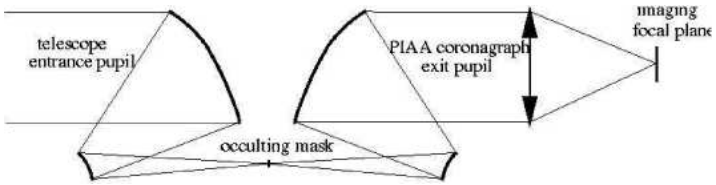


Figure: Schematic of a PIAA system. [Guyon, 2003]

Figure: Pupil mask for high contrast imaging. [Vanderbei et al., 2003]

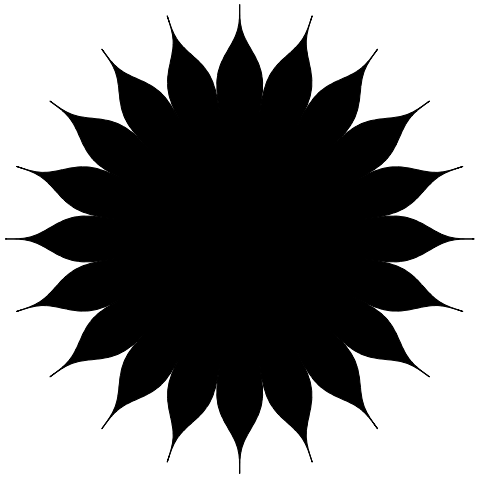


Figure: Proposed star-shade design. [Spergel et al., 2009]

Instrument Outputs and Constraints

[Brown, 2005, Lindler, 2007]

- Limiting Δmag - maximum achievable difference in brightness between star and planet.
- Inner working angle (IWA) - minimum angular separation between a star and planet.

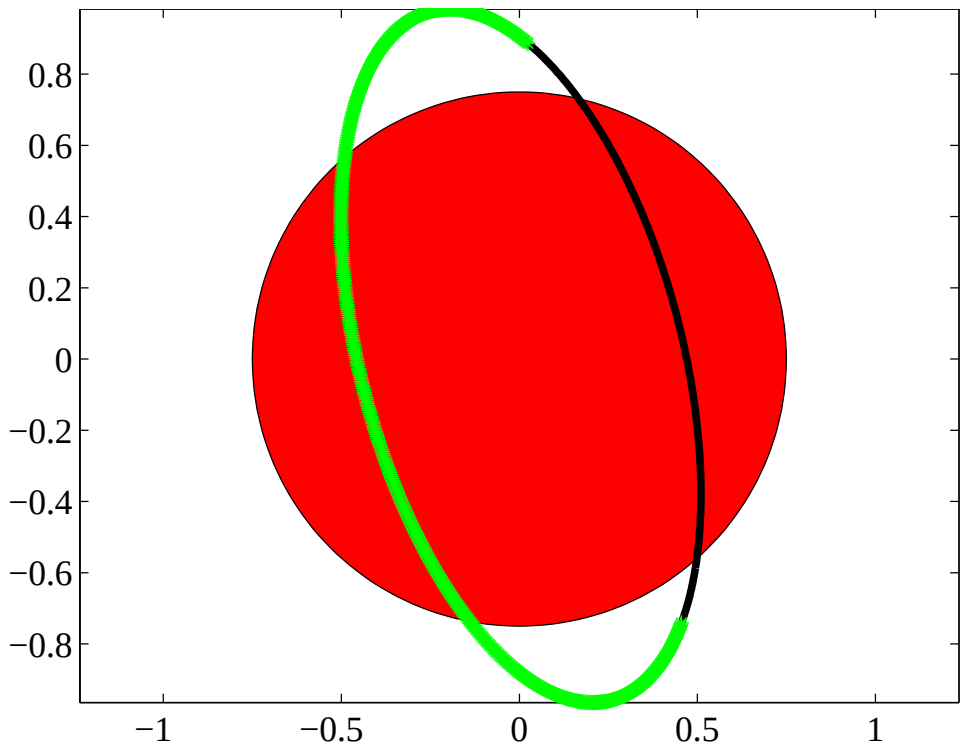


Figure: Schematic of a planetary observation.

- The red circle represents the instrument's projected IWA.
- The planet is sufficiently illuminated only on the green portion of the orbit.
- Detection occurs on the green part of the orbit outside the red circle.

Mission Analysis

- Create descriptions of instruments, planetary orbits/properties and observations.
- Generate full mission simulations (timelines of observations and their outcomes).
- From these mission ensembles, extract distributions of science yield/performance metrics:
  - All Detections - Total number of successful planetary observations throughout a whole mission simulation (includes repeat detections).
  - Unique Detections - Number of individual planets found during a mission simulation.
  - Unique Targets - Number of individual stars observed during a mission simulation.
  - Spectral Characterizations - Number of observations where the planet was observable for sufficient time to integrate to a predefined S/N level.
  - Propellant Used - For occulters, the amount of propellant used by the starshade for slewing and stationkeeping.

Visits as a Graph

[Savransky and Kasdin, 2008]

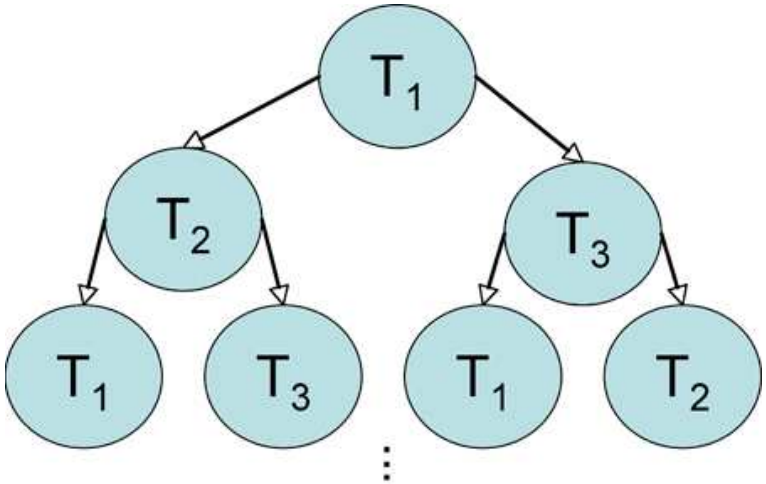


Figure: Visit graph for 3 target pool.

- Each set of possible transitions on the visit graph can be represented as a weighted adjacency matrix.
- The weights of the matrix entries represent the 'cost' of choosing the next star.

The cost of transitioning from target i to target j is calculated as:

$$A_{ij} = \left[\begin{array}{c} a_1 \frac{\cos^{-1}(u_i \cdot u_j)}{2\pi} B_{inst} + a_2 \mathrm{comp}_j - a_3 e^{t-t_f} B_{unvisited} + \\ a_4 B_{visited}(1 - B_{revisit}) - a_5 B_{revisit} \left(\frac{N_j}{N_{req}} \right) (N_j < N_{req}) - a_6 \frac{\tau_j}{\mathrm{vis}_j} \end{array} \right] (1 - B_{ko})$$

Automated Visit Order

- The amount of time spent on any one target depends on whether a planet is detected.
- The adjacency matrix must be continuously updated.

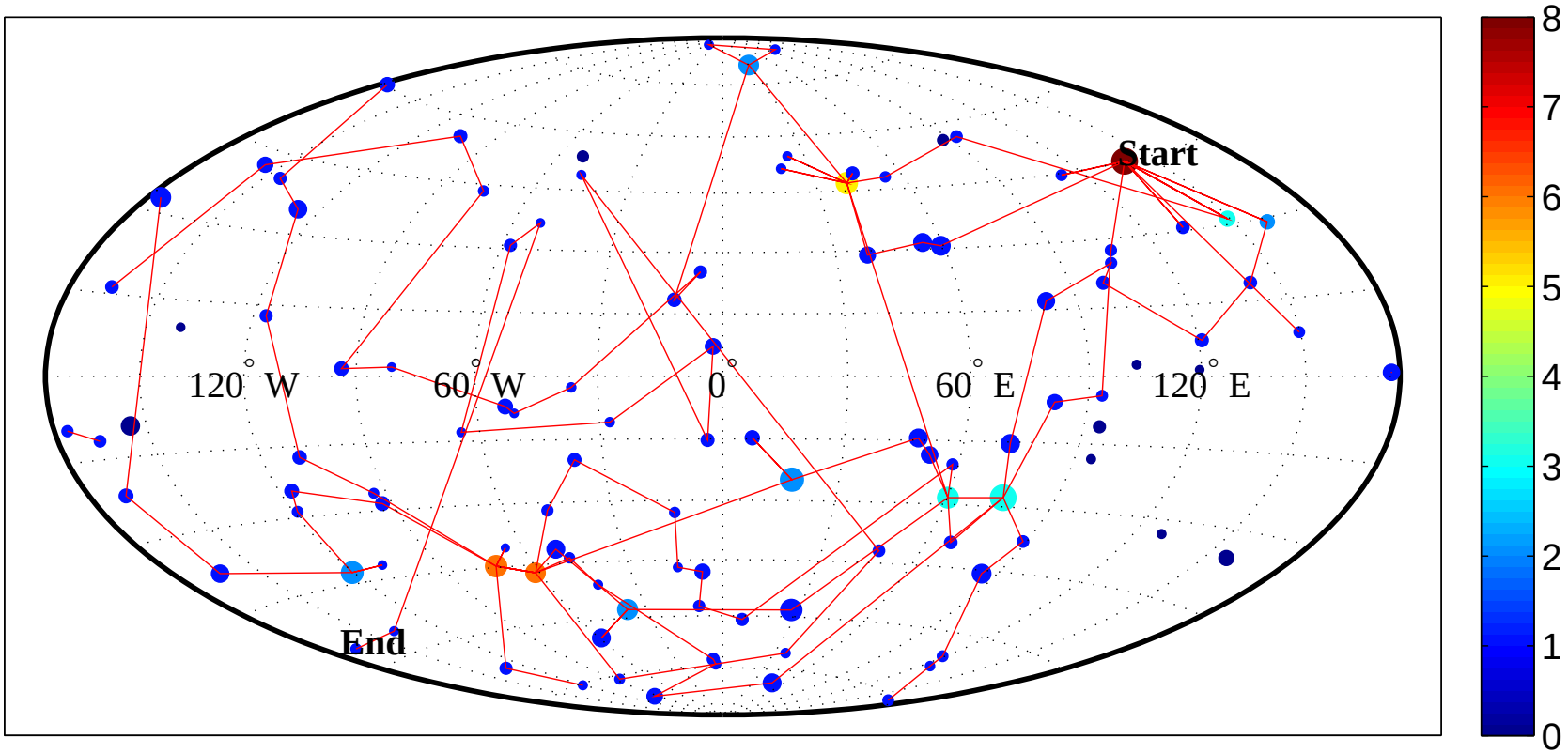


Figure: Automatically generated visit order.

Outline

Test Cases and Requirements

Common Elements

- 1, 4, 8, 16m circular telescope
- 5 year mission
- Launch vehicle capacity = 6300kg (or unlimited)
- High QE, low readnoise CCDs
- Same propulsion subsystems for all occulters.

2,3 λ/D Internal Coronograph

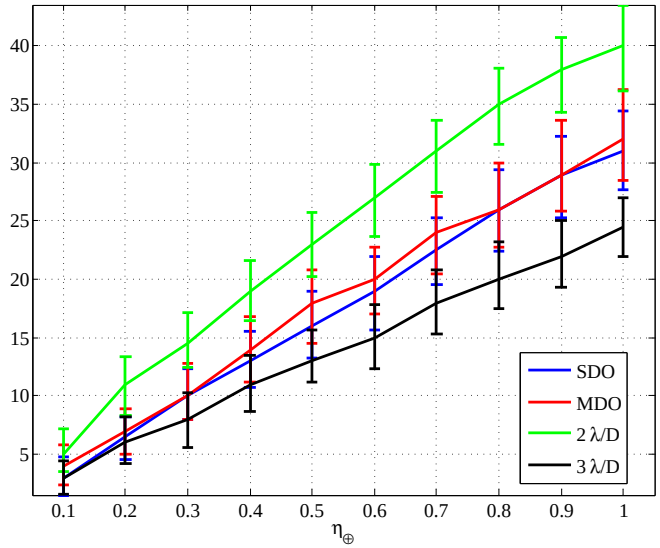
- Idealized PIAA
- Maximum throughput of 0.8
- Simultaneously maximize number of visited targets and probability of detecting planets with importance weighting of 2:1 towards finding planets.
- Acquire one full spectrum (250-1000nm) for each uniquely found planet, to SN = 11 at 760nm O_2 line, with R = 70.
- Attempt at least four detections of each discovered planet at orbital separations of at least 10°.

Occulter Test Cases

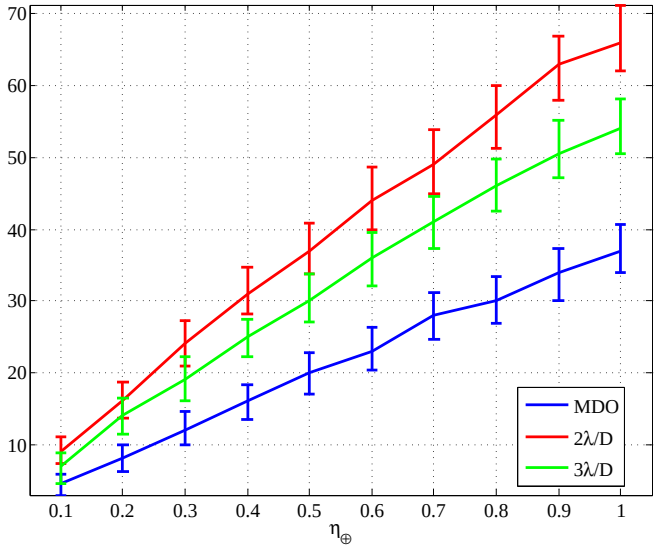
Telescope Diameter (m)	Occulter Type	Starshade Radius (m)	Separation Distance (km)	50% Throughput IWA (mas)
4	SDO	25.6	70400	59
	MDO	20	55000/35000	57.5
8	SDO	35.2	96800	56
	MDO	27.2	74800/52360	53
16m	MDO	43.2	118800/83160	47

Telescope Diameter (m)	Occulter Type	Starshade Mass (kg)	Petal Length (m)
4	SDO	4200	19
	MDO	3370	10
8	SDO	7180	24
	MDO	4915	13.5
16m	MDO	10022	21.5

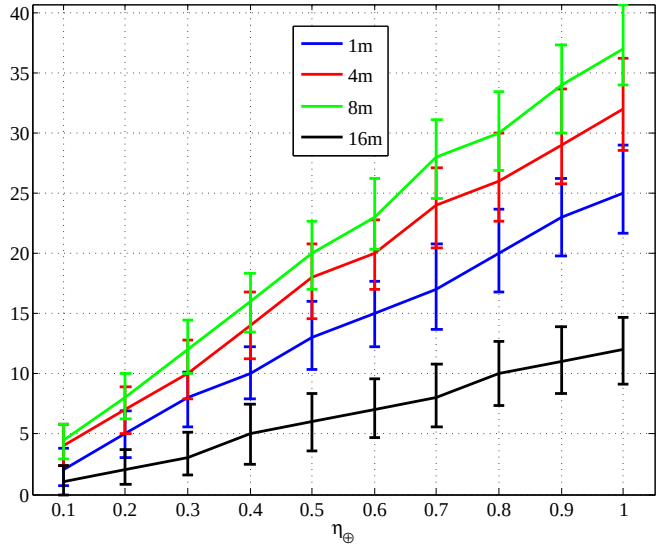
Comparison of Mission Concepts - Unique Detections



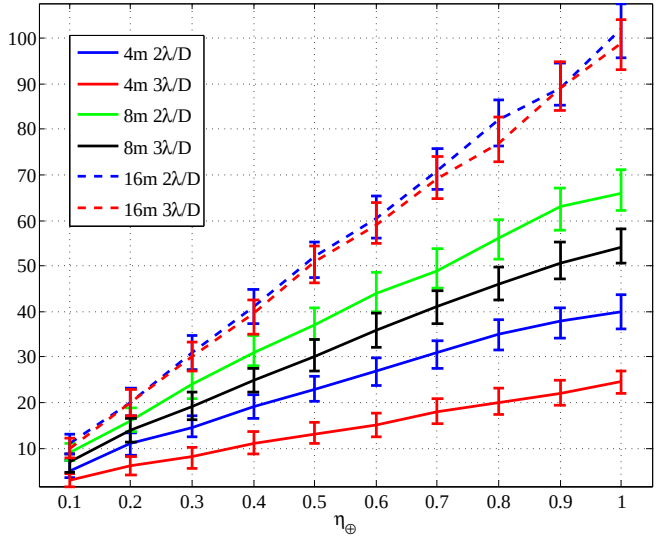
4 m Telescope



8 m Telescope



MDOs



Coronagraphs

Comparison of Mission Concepts - Summary at $\eta_\oplus = 1$

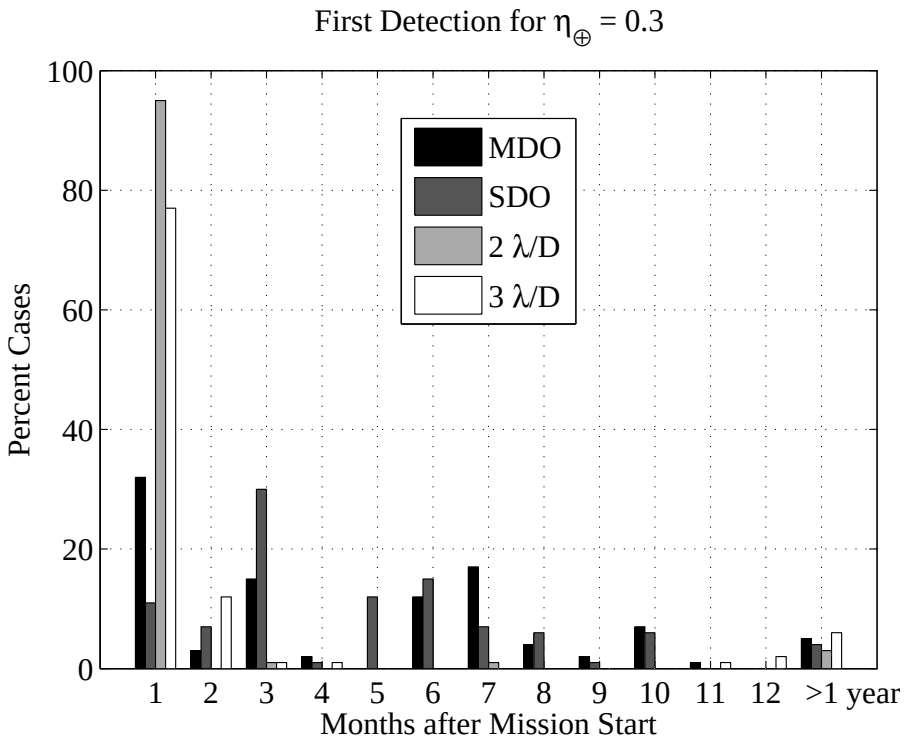
Unique Detections

	SDO	MDO	$2\lambda/D$	$3\lambda/D$
1 m	X	25	X	X
4 m	31	32	40	25
8 m	18	37	66	54
16 m	X	12	102	99

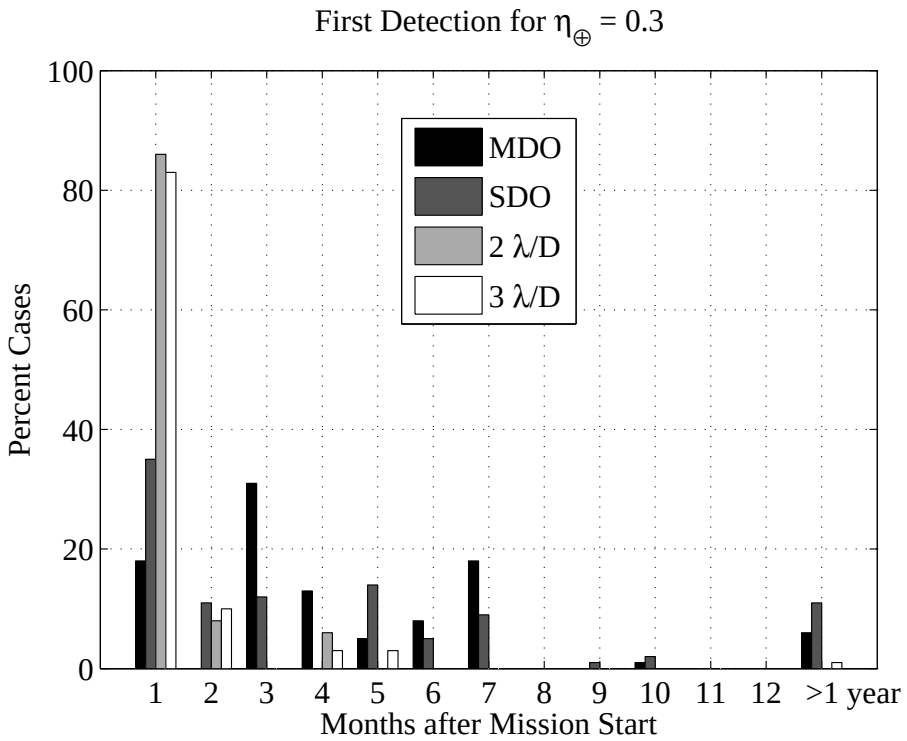
Full Spectra

	SDO	MDO	$2\lambda/D$	$3\lambda/D$
1 m	X	7	X	X
4 m	24	18	17	5
8 m	15	18	44	24
16 m	X	6	96	80

First Detections



4 m Telescope



8 m Telescope

Conclusions

- At 4m scale, occulter and coronagraph performances are comparable.
  - Coronagraphs will get more total detections.
  - Occulters will produce more full spectra.
- A 1 to 2 m telescope with an occulter is a viable option for Earth-twin finding.
- At 8m and above, coronagraphs outperform single occulters - need to study multiple occulter systems and better propulsion systems.
  [Hunyadi et al., 2007]
- Coronagraphs are likely to produce results earlier in the mission than occulters.
- More study is needed on putting together the best possible target lists.

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Local Optimality of Decision Modeling

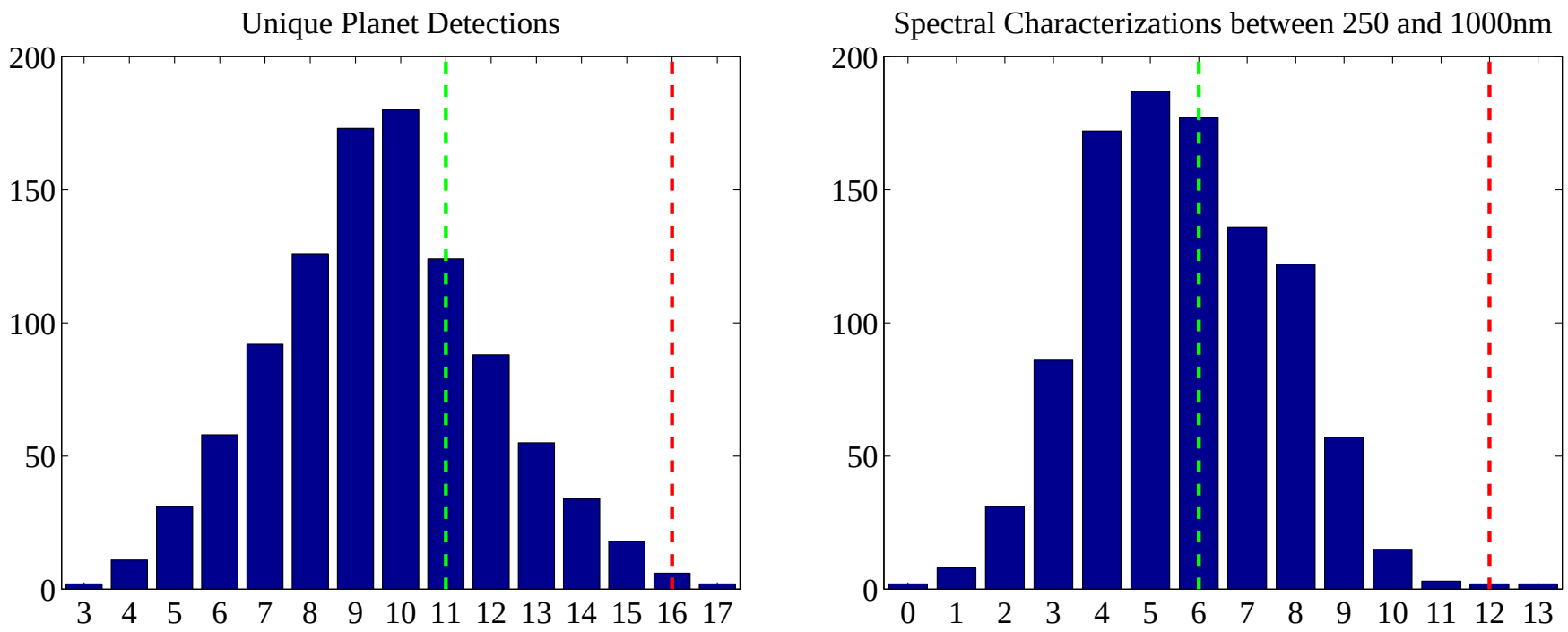


Figure: Comparison of scientific yield from automated visit order selection and randomized visit order. The blue bars are histograms of results from 1000 mission simulations using randomized visit order in one universe. The red dashed lines are results from the automated visit order for the same universe, and the green dashed lines are results obtained by always going to the next highest completeness target.

Local Optimality of Decision Modeling

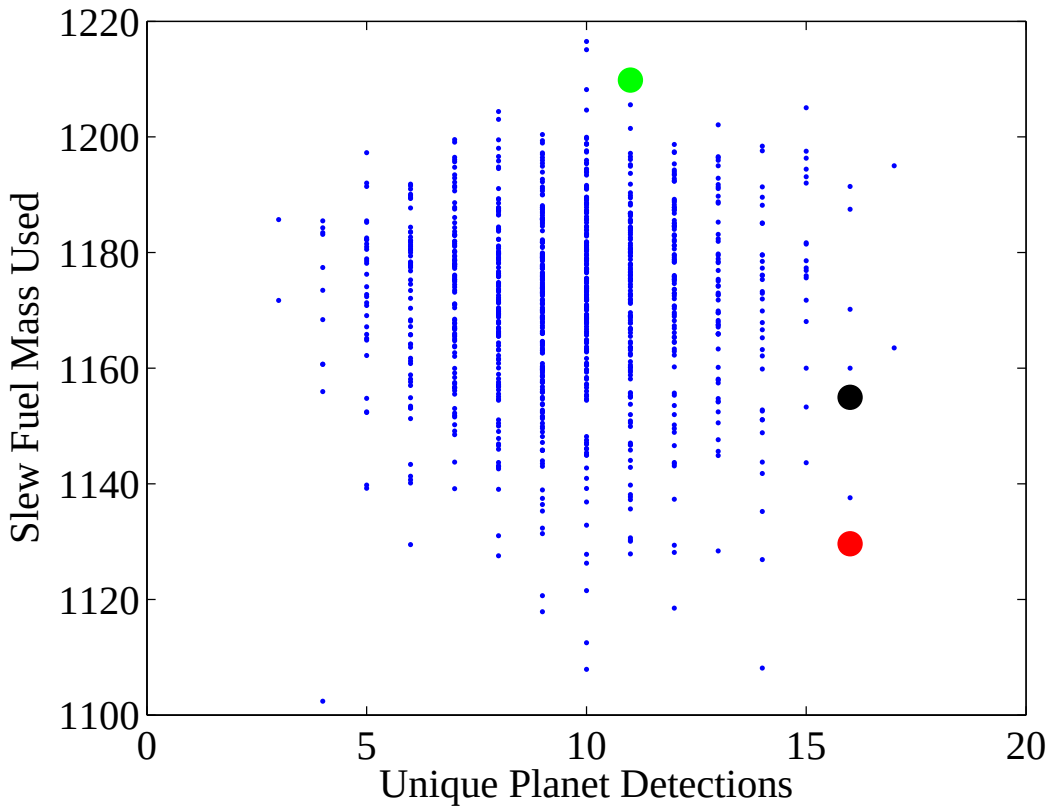
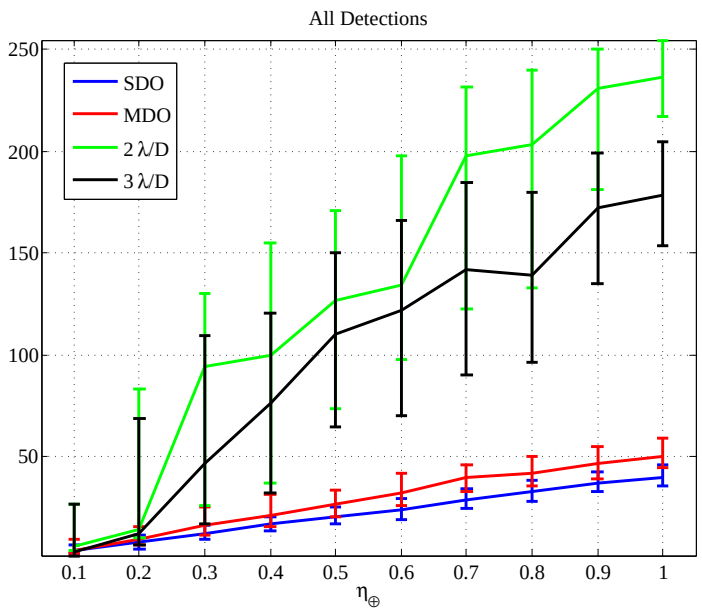


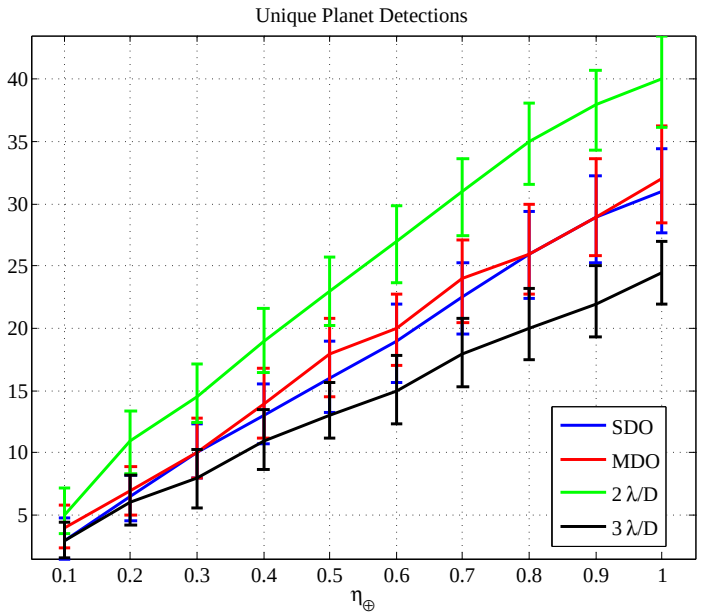
Figure: Occulter propellant use (in kg) vs. the number of unique planet detections for 1000 mission simulations using randomized visit order in one universe. The red point represents the mission generated using the automated visit order for the same universe and the green point represents the mission generated by always going to the next highest completeness target.

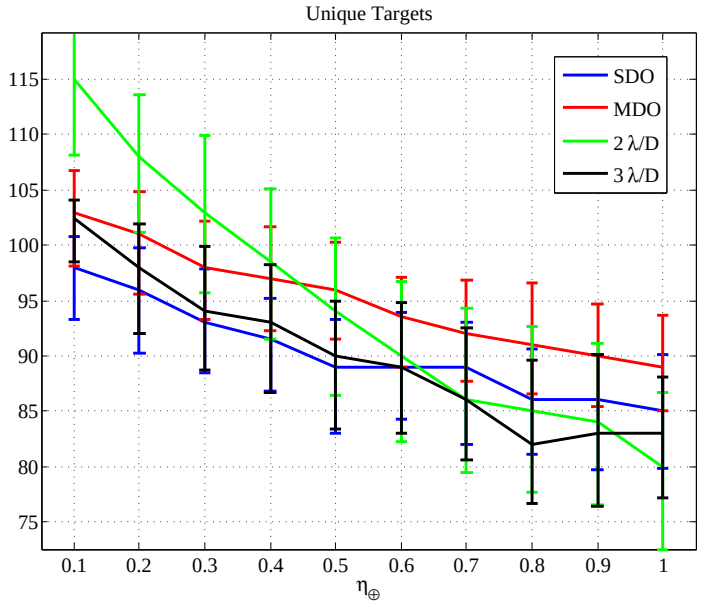
Observation Times and Target Pools

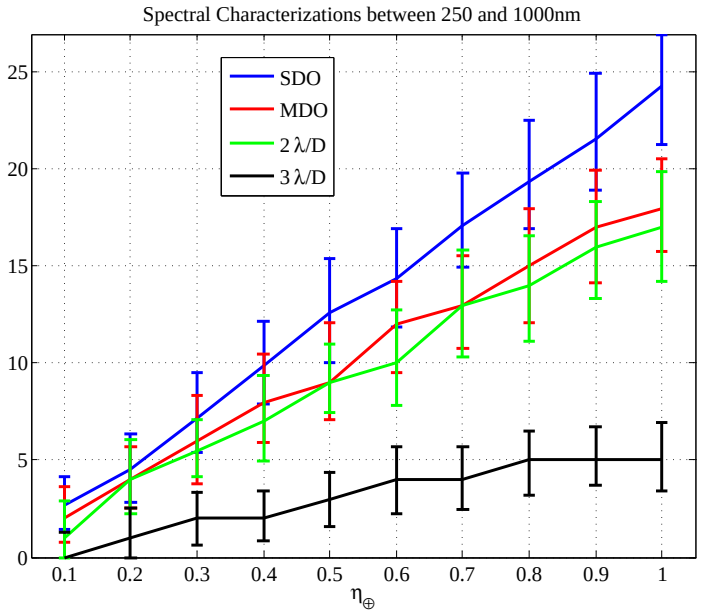
Telescope Diameter (m)	Suppression System	Mission Portion	Available Targets
4	SDO	19%	112
	MDO	20%	117
	2 λ/D	50 %	173
	3 λ/D	50 %	110
8	SDO	7%	140
	MDO	8%	157
	2 λ/D	50 %	253
	3 λ/D	50 %	230
16	MDO	4%	242
	2 λ/D	50 %	385
	3 λ/D	50 %	351

Comparison of Mission Concepts with 4m Telescope

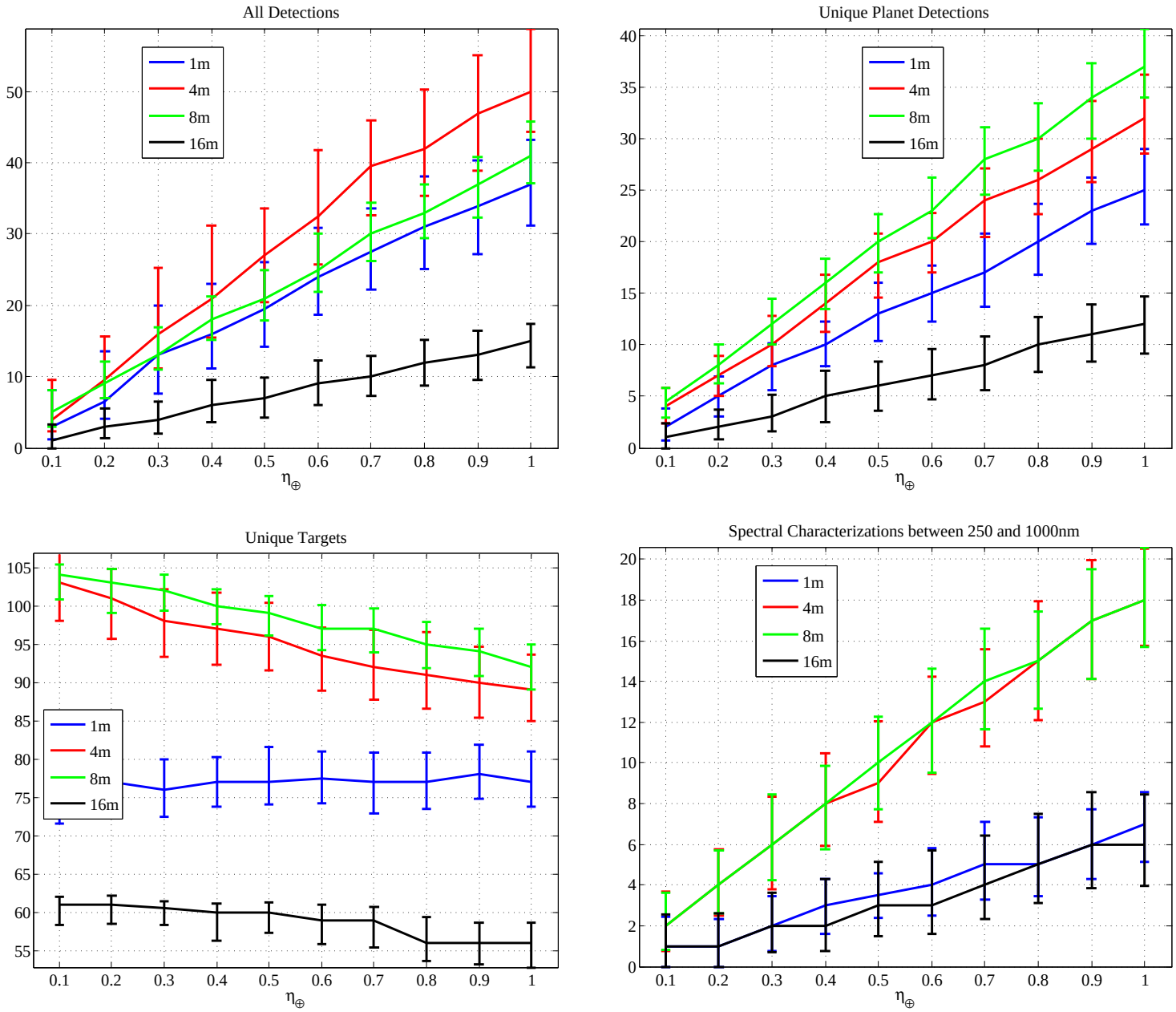




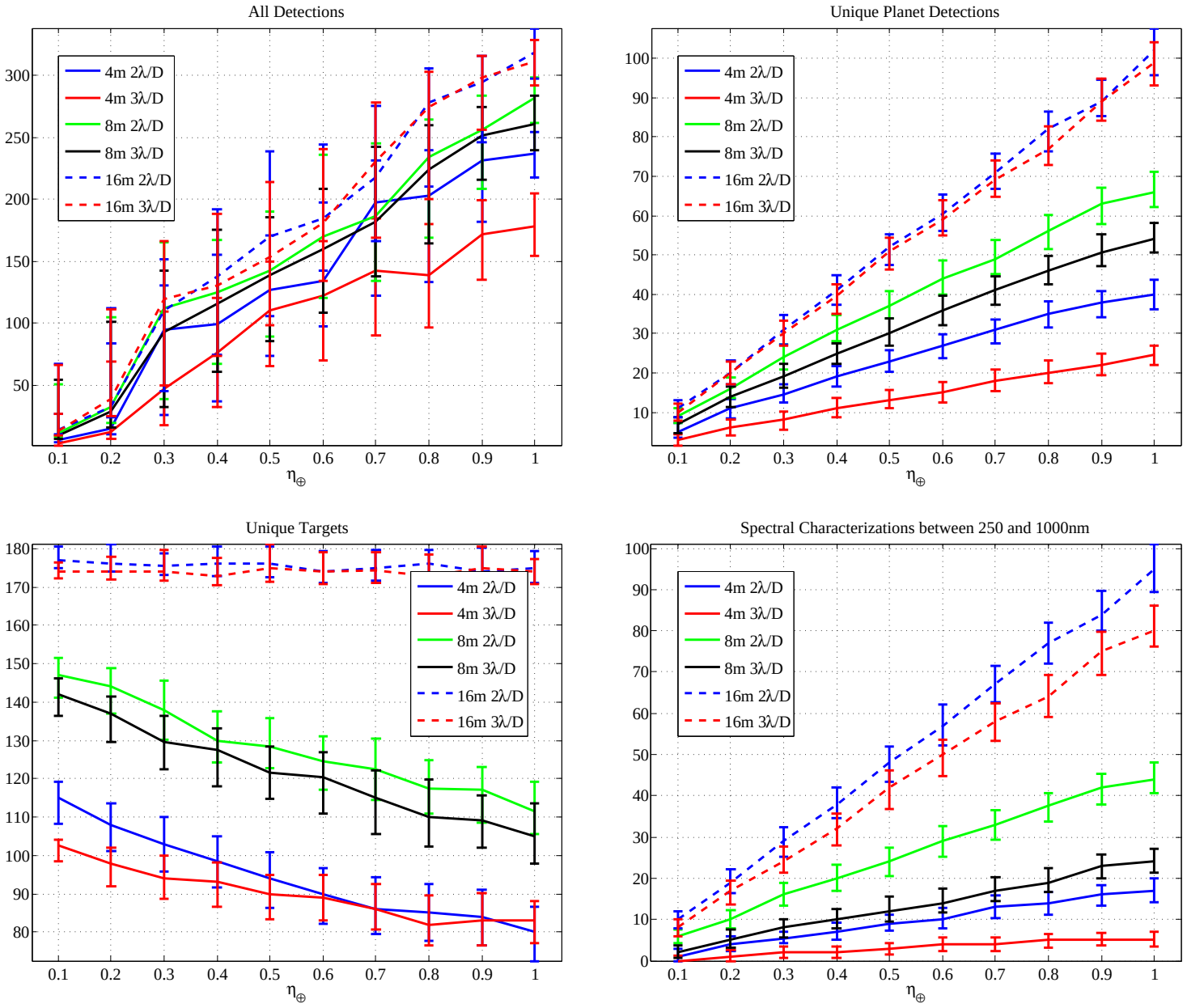




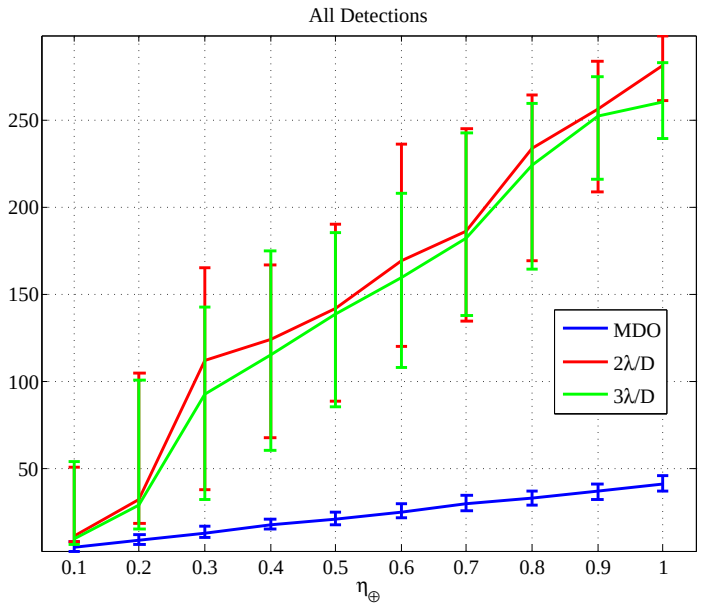
Comparison of Multiple Distance Occulters Systems

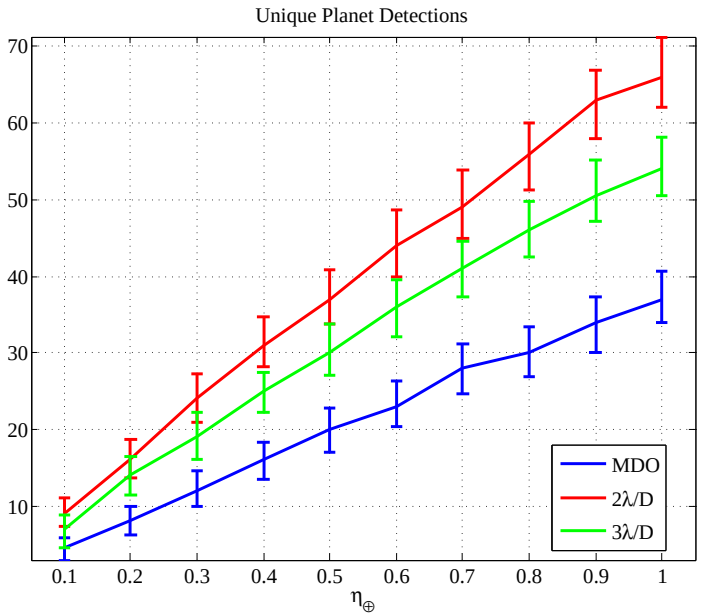


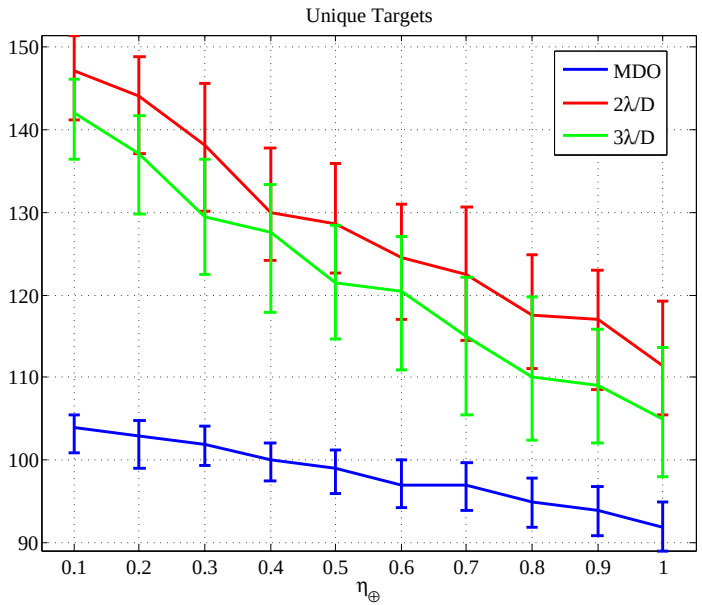
Comparison of Coronagraph Systems

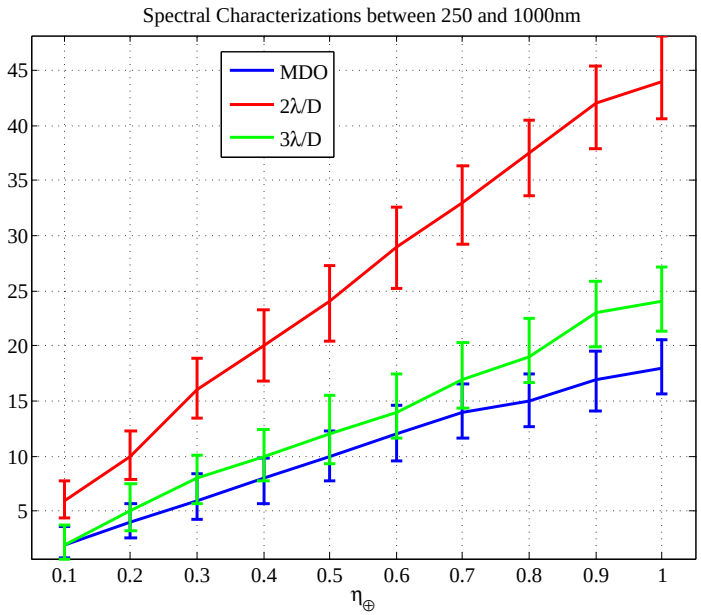


Comparison of of Mission Concepts with 8m Telescope

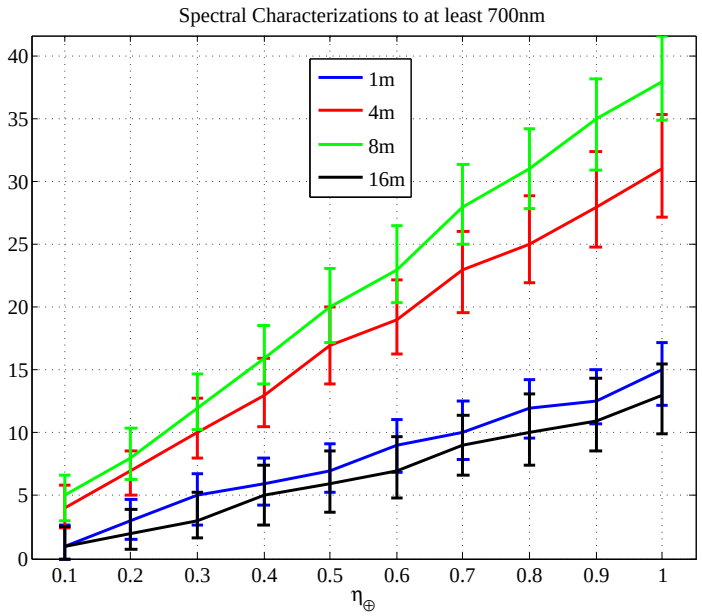


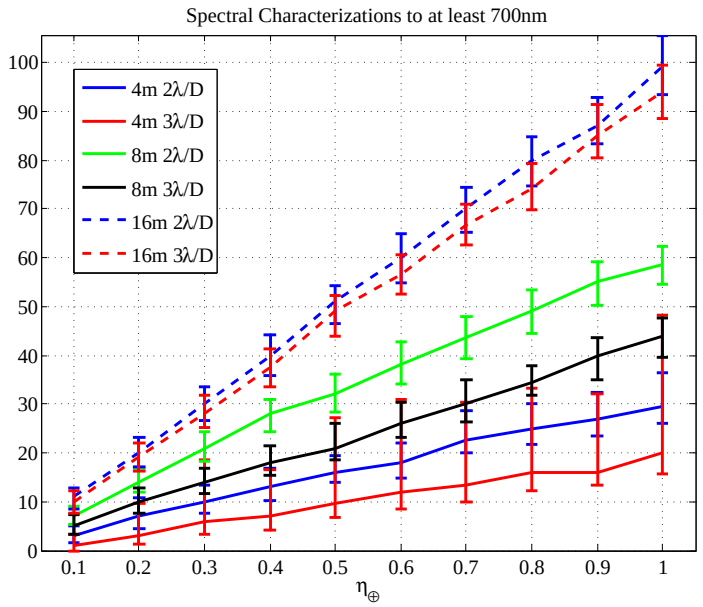


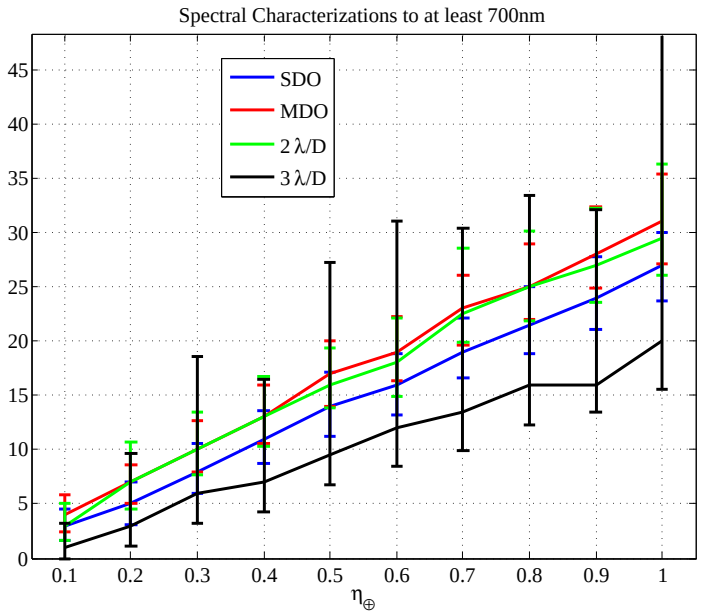


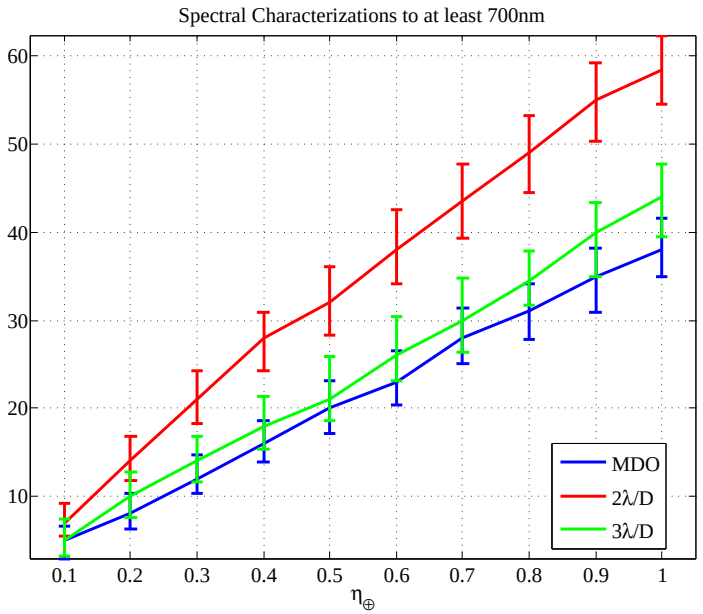


Partial Spectra









Repeated Detections

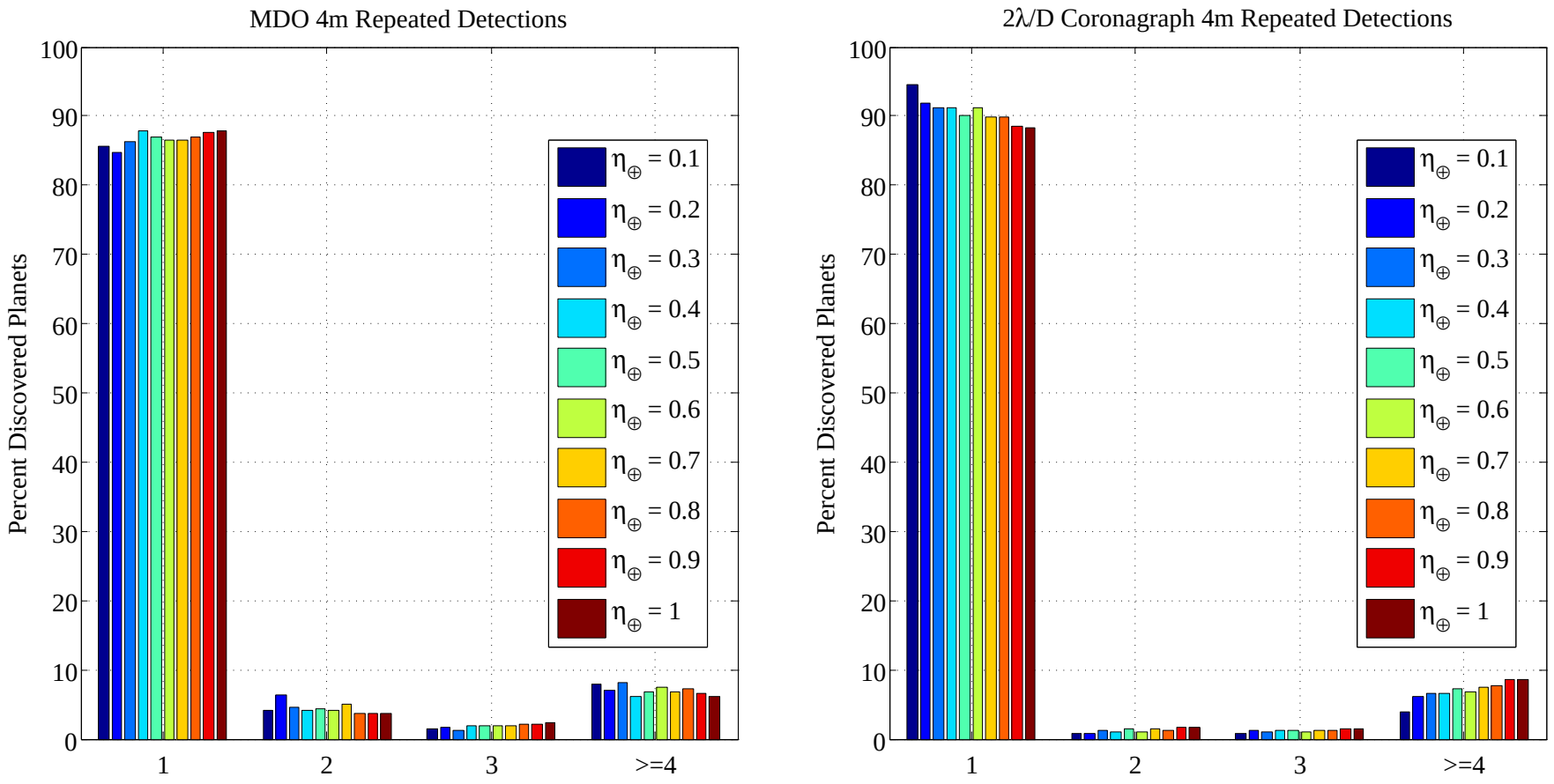
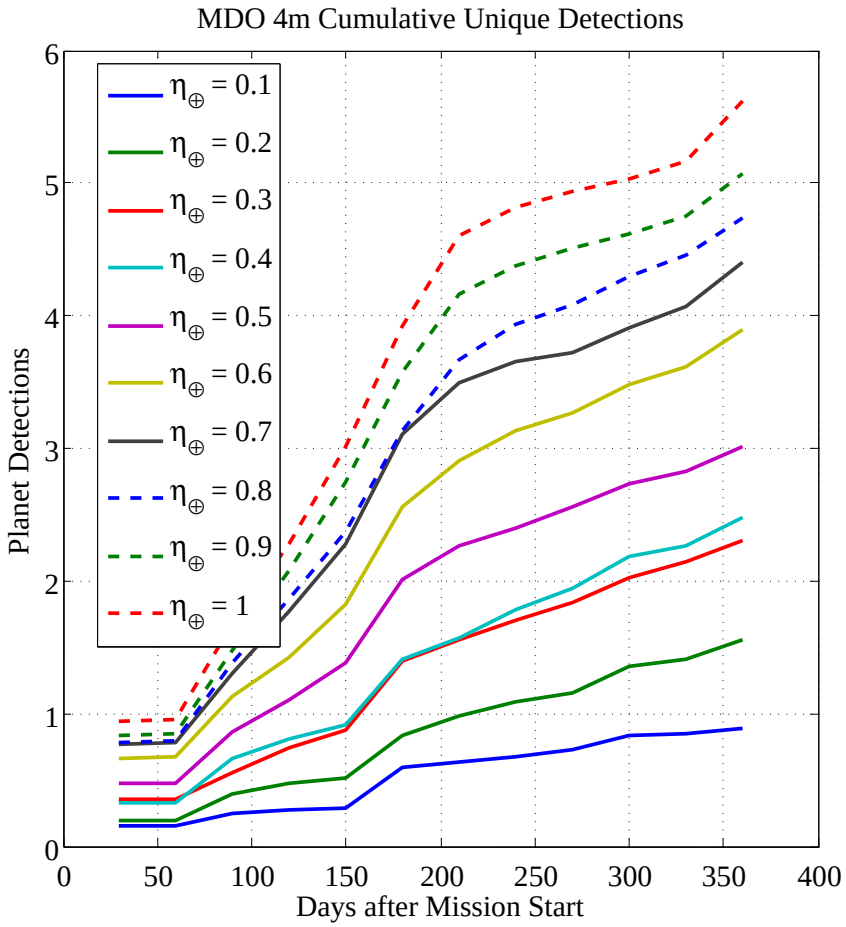
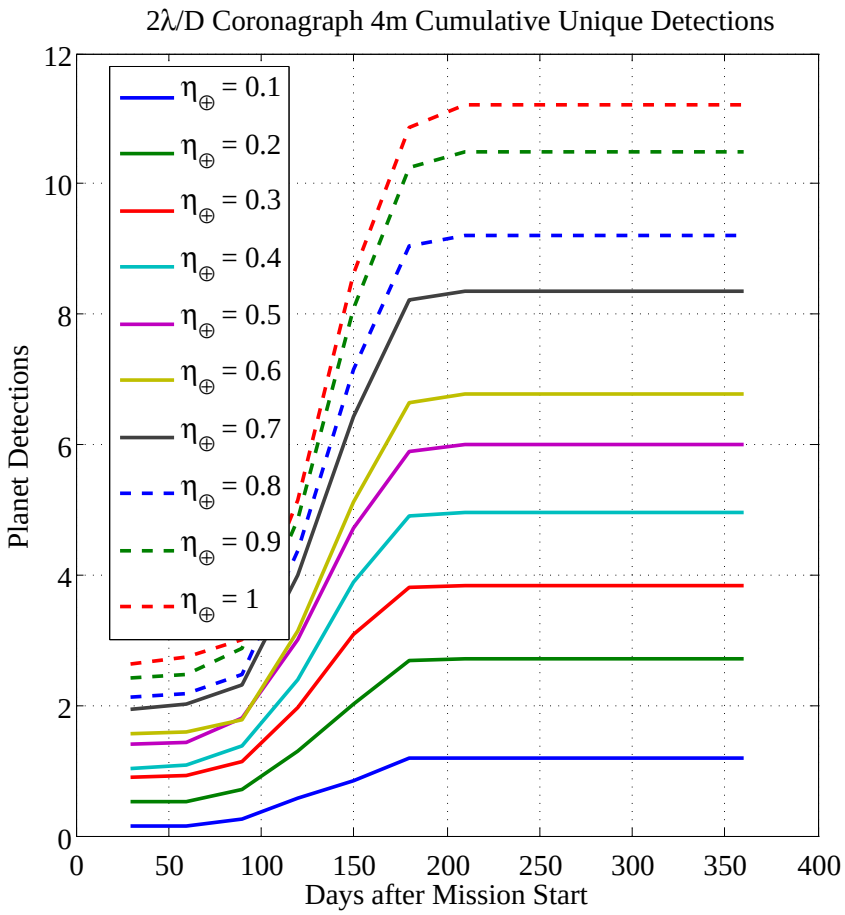


Figure: Histograms of percent detected planets with repeated detections.

Cumulative Unique Detections in First Year





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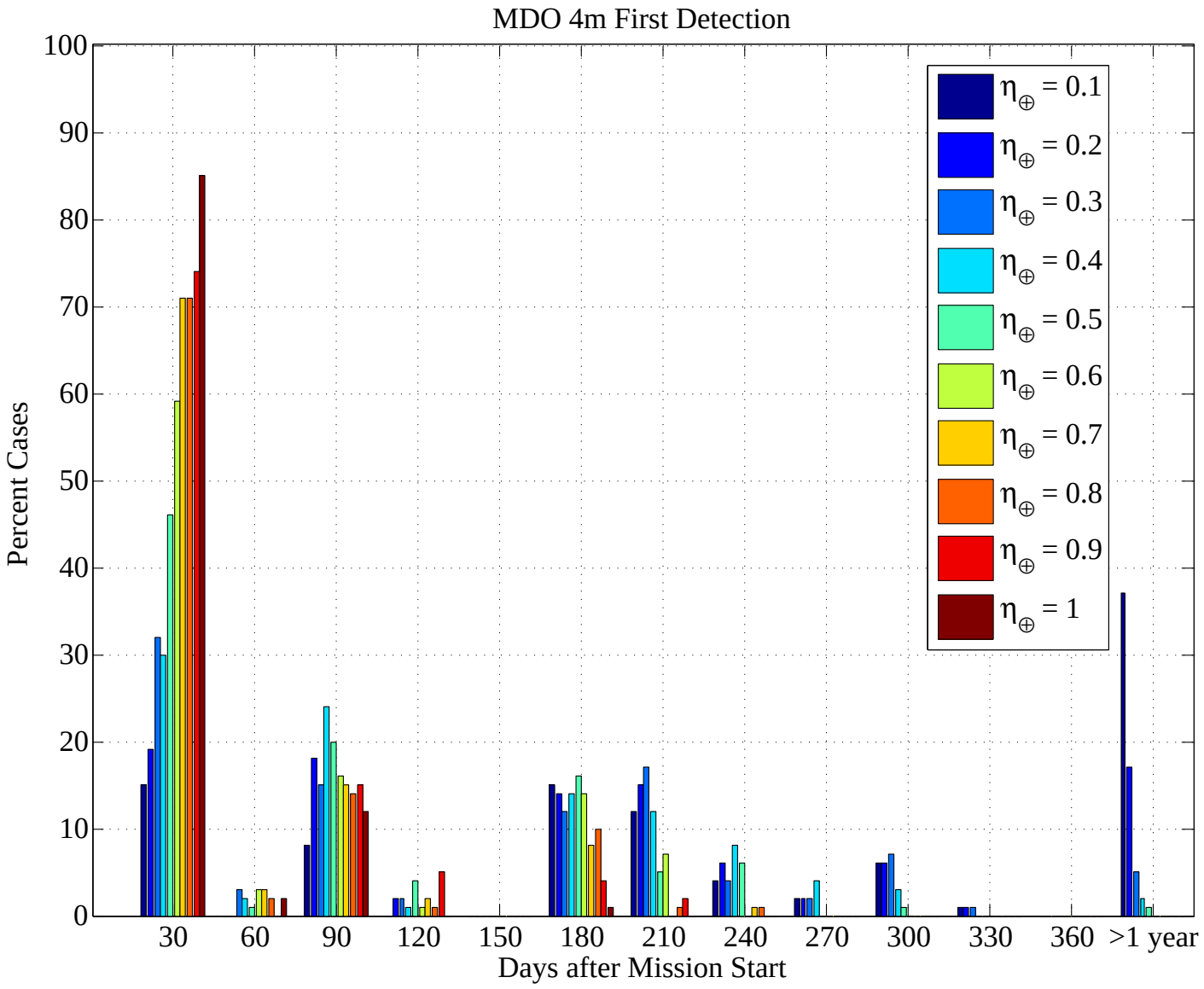
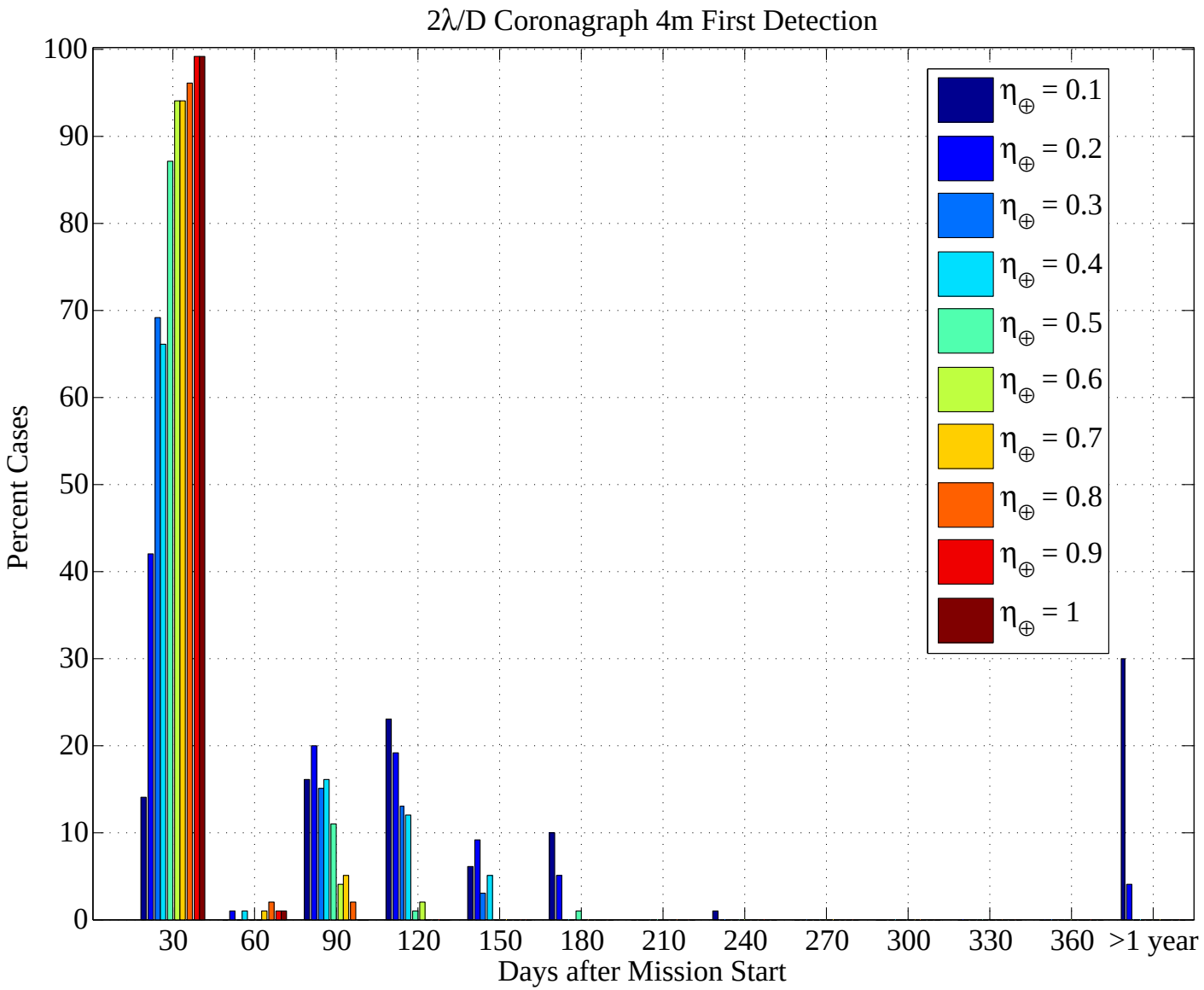
First Detection for 4m MDO



First Detection for 4m 2 λ/D Coronagraph



First Detection for 4m 3 λ/D Coronagraph