Quantifying the impacts of schedulability on science yield of exoplanet imaging missions

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A Very Important Paper

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SINGLE-VISIT PHOTOMETRIC AND OBSCURATIONAL COMPLETENESS

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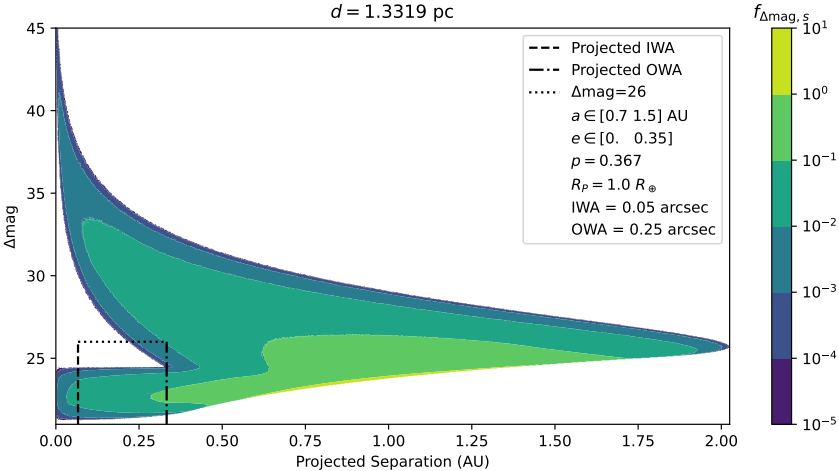
ABSTRACT

We report a method that uses "completeness" to estimate the number of extrasolar planets discovered by an observing program with a direct-imaging instrument. We develop a completeness function for Earth-like planets on "habitable" orbits for an instrument with a central field obscuration, uniform sensitivity in an annular detection zone, and limiting sensitivity that is expressed as a "delta magnitude" with respect to the star, determined by systematic effects (given adequate exposure time). We demonstrate our method of estimation by applying it to our understanding of the coronagraphic version of the *Terrestrial Planet Finder* (*TPF-C*) mission as of 2004 October. We establish an initial relationship between the size, quality, and stability of the instrument's optics and its ability to meet mission science requirements. We provide options for increasing the fidelity and versatility of the models on which our method is based, and we discuss how the method could be extended to model the *TPF-C* mission as a whole to verify that its design can meet the science requirements.

Subject headings: instrumentation: high angular resolution — planetary systems — techniques: high angular resolution

Photometric and Obscurational Completeness



$$c = \int_{\tan(\mathrm{IWA})d}^{\tan(\mathrm{OWA})d} \int_0^{\Delta\mathrm{mag}_{\mathrm{lim}}(s)} f_{\bar{s},\overline{\Delta\mathrm{mag}}}\left(s, \Delta\mathrm{mag}\right)\, \mathrm{d}\Delta\mathrm{mag}\, \mathrm{d}s$$

See: Brown, "Single-visit photometric and obscurational completeness", 2005; Garrett and Savransky, "Analytical Formulation of the Single-visit Completeness Joint Probability Density Function", 2016

Predicting Exoplanet Yield: Summed Completeness

Expected number of exoplanet detections for n target stars:

$$E[\text{detections}] = \eta \sum_{k=1}^{n} k \sum_{j \in {}_nC_k} \prod_{i \in j} p_i \prod_{i \notin j} (1 - p_i) = \eta \sum_{i=1}^{n} p_i$$

Planet Occurrence Rate

Combinations of $\{i\}_{i=1}^{n}$ Taken k at a Time

Probability of Planet Detection at ith Target

- Pro: (Relatively) Straightforward to compute
- Con: Need a separate probability calculation for every metric of interest
- Pro and Con: Can get a result without actually scheduling observations

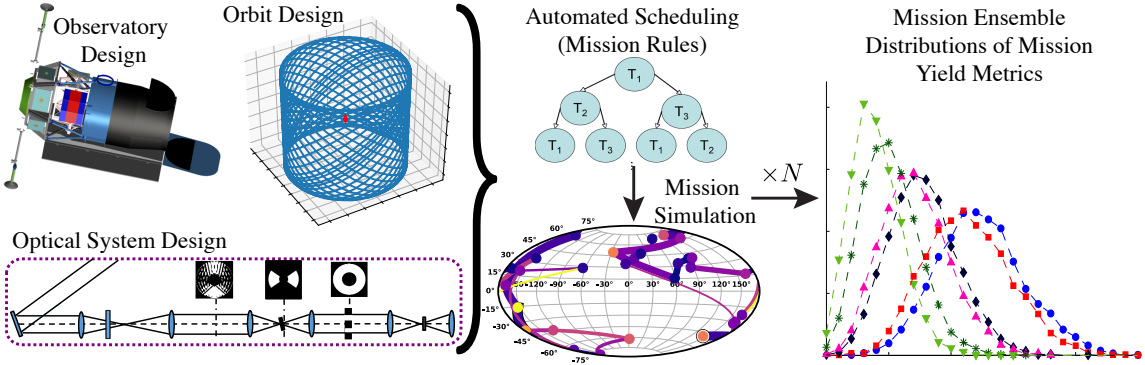
See: Brown, "Single-visit photometric and obscurational completeness", 2005; Garrett, Savransky, and Macintosh, "A Simple Depth-of-Search Metric for Exoplanet Imaging Surveys", 2017

Brown, Again

The highly contingent nature of an observing program for extrasolar planets demands a new level of simulations for mission verification. This new level must involve Monte Carlo simulations of the mission as a whole.

Brown, "Single-visit photometric and obscurational completeness", 2005

Predicting Exoplanet Yield: Monte Carlo Mission Modeling

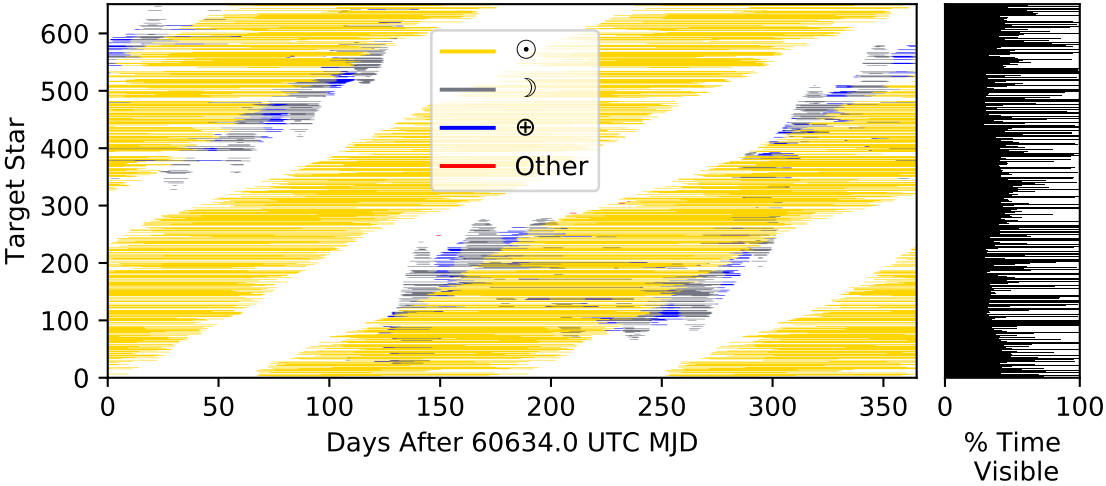


- Pro: Can extract effectively *any* metric of performance with errorbars
- Con: Computationally costly

- Pro and Con: Requires a mission schedule

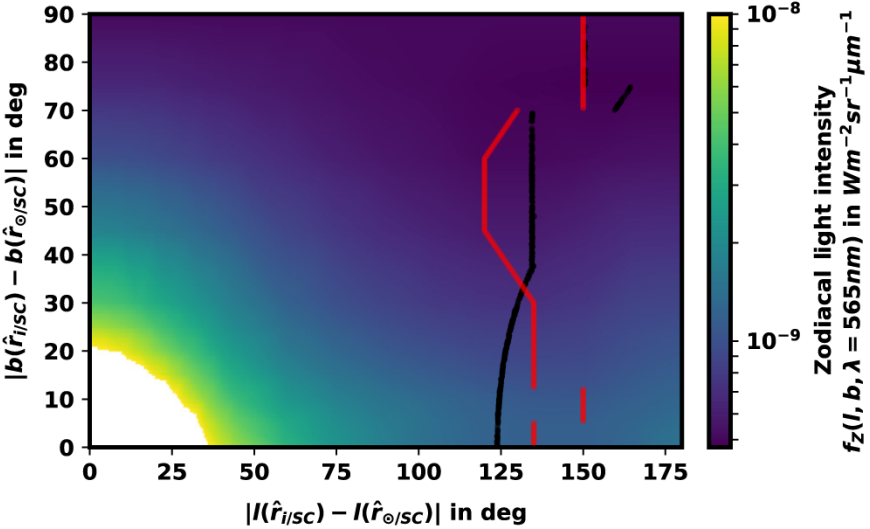
See: Savransky, Kasdin, and Cady, "Analyzing the designs of planet finding missions", 2010; Savransky and Garrett, "WFIRST-AFTA coronagraph science yield modeling with EXOSIMS", 2015

Scheduling Constraints: Keepout



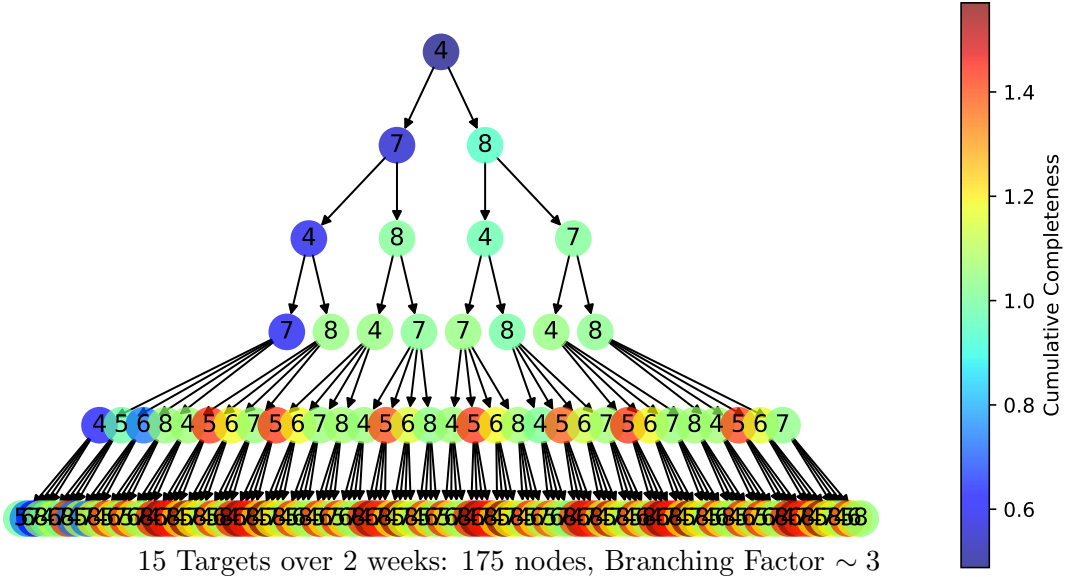
Targets are observable in white regions of the graph. The sun keepout may be due to direct sun avoidance, starshade glint avoidance, or solar panel pointing restrictions.

Scheduling Constraints: Local Zodiacal Light



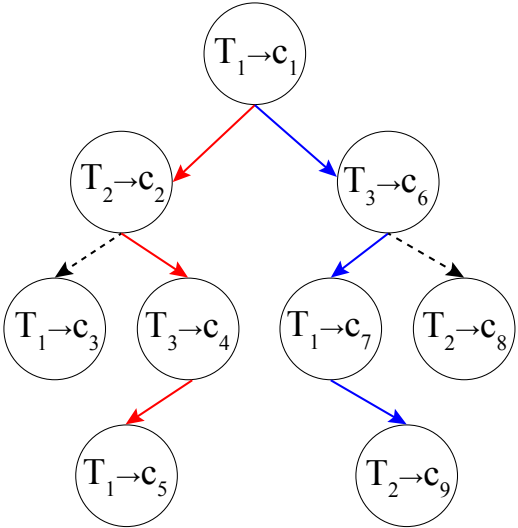
From Keithly et al., "Optimal scheduling of exoplanet direct imaging single-visit observations of a blind search survey", 2020 based on Leinert et al., "The 1997 reference of diffuse night sky brightness", 1998.

Mission Schedules as Directed Acyclic Graphs



15 Targets over 2 weeks: 175 nodes, Branching Factor ~ 3

Pruning the Search Graph

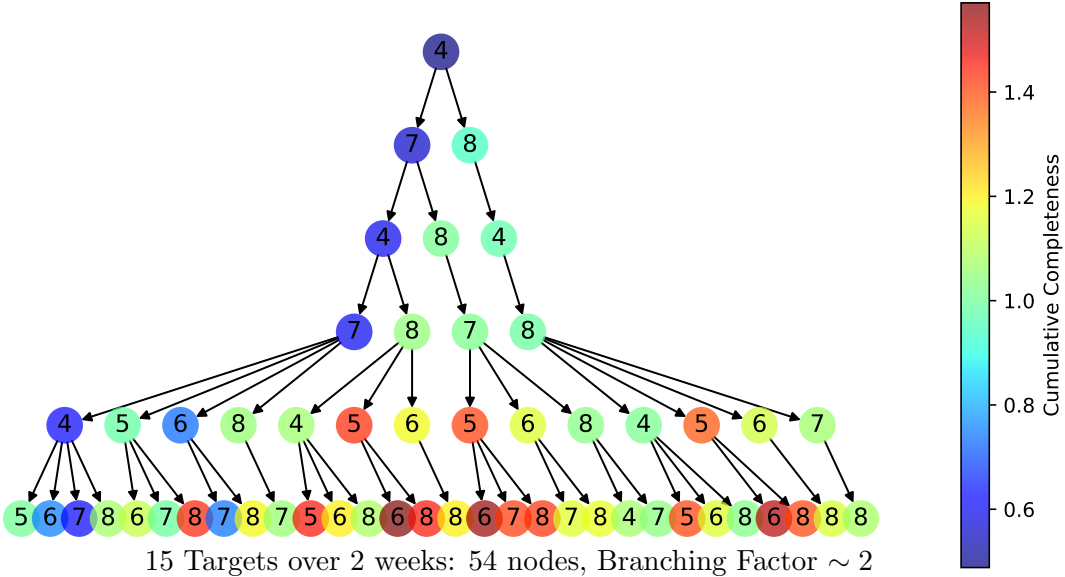


- We can enumerate more schedule options by pruning equivalent branches
- Equivalency is determined by ignoring target order and tracking accumulated completeness from the same set of targets
- For example: red $\equiv$ blue iff

$$c_1 + c_2 + c_4 + c_5 = c_1 + c_6 + c_7 + c_9$$

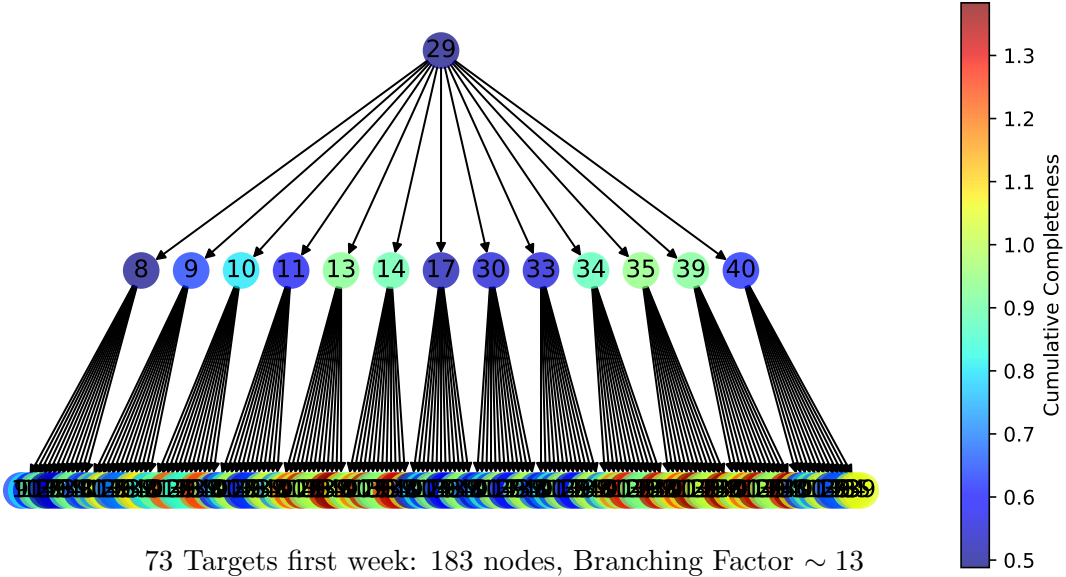
- Round completeness to the second decimal place

Pruning in Action



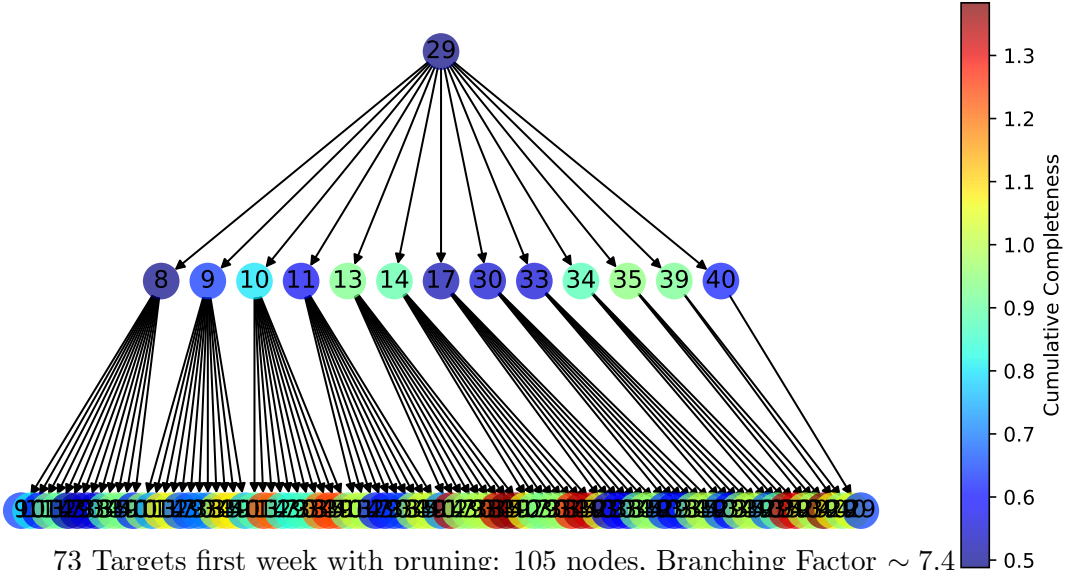
15 Targets over 2 weeks: 54 nodes, Branching Factor ~ 2

A More Realistic Example



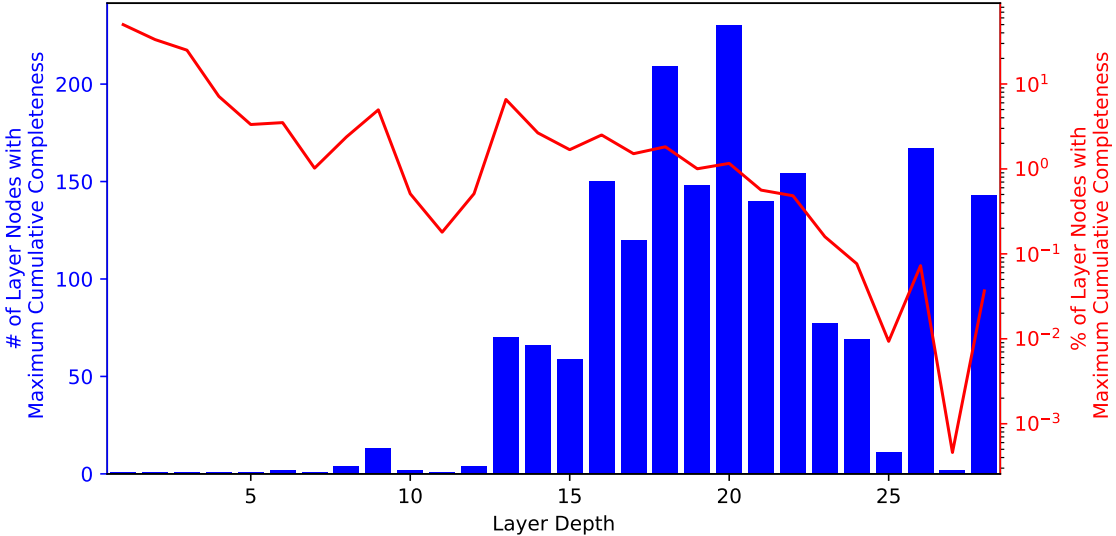
73 Targets first week: 183 nodes, Branching Factor ~ 13

A More Realistic Example



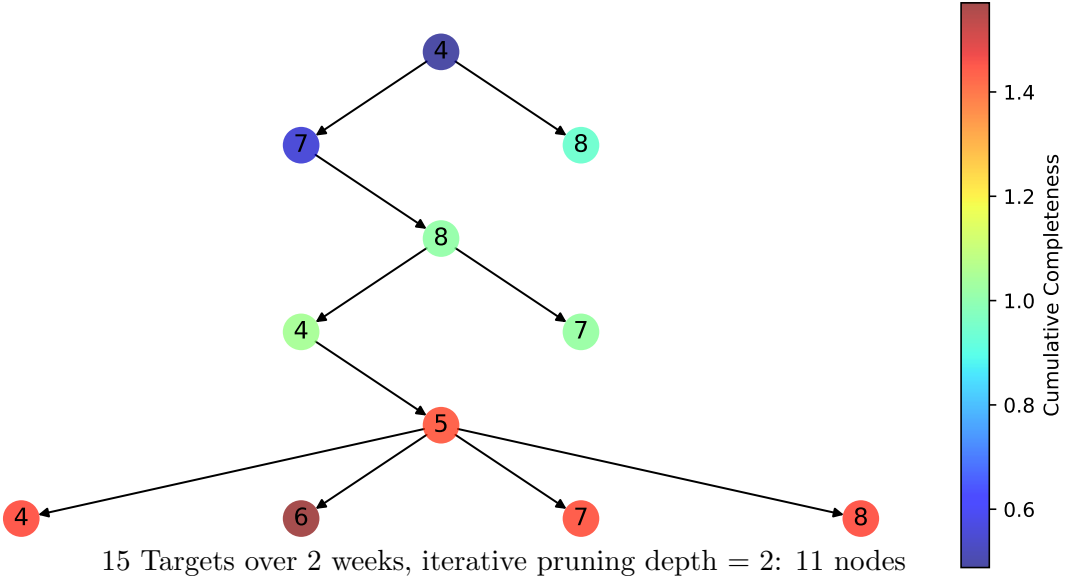
73 Targets first week with pruning: 105 nodes, Branching Factor ~ 7.4

Maximum Cumulative Completeness By Layer



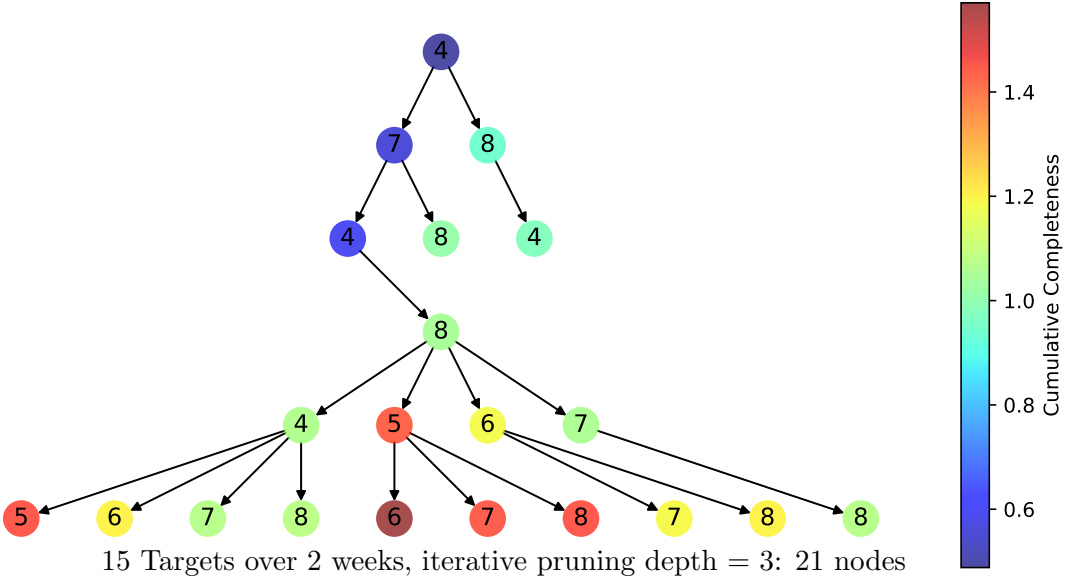
15 Targets over 60 days

More Aggressive Pruning



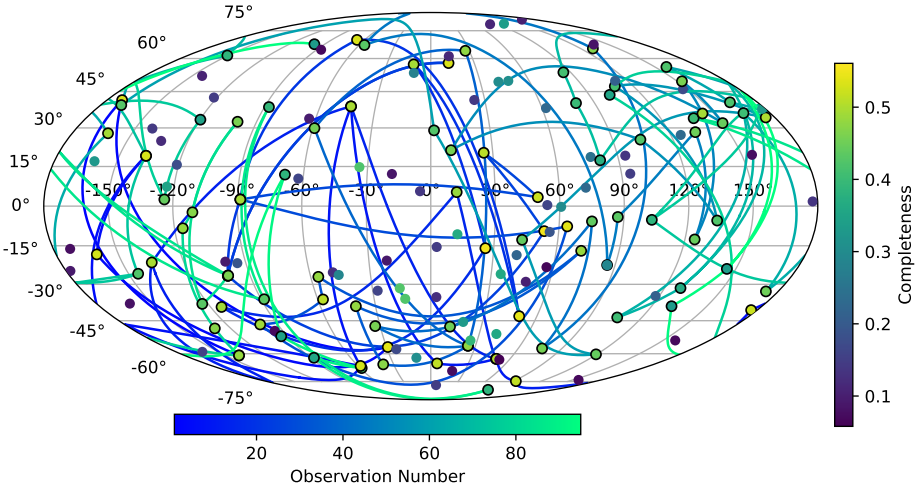
15 Targets over 2 weeks, iterative pruning depth = 2: 11 nodes

More Aggressive Pruning



15 Targets over 2 weeks, iterative pruning depth = 3: 21 nodes

Some Validation



- 1 year of observations with 3.25 days overhead per observation

- Max summed completeness of 46.24 for 102 targets assuming min local zodi (33 days of integration)
- Best observing schedule has summed completeness of 43.85 with 96 targets (53 days of integration)

Conclusions

- The average branching factor for mission scheduling graphs is typically between **one fifth** and **one third** the size of the target list
- Pruning equivalent paths reduces the original branching factor by an average factor of **2**
- Retaining only maximum cumulative completeness paths every k topological levels of the graph produces different 'optimal' paths, but with nearly equivalent summed completeness
- In cases tested so far, scheduling constraints appear to reduce maximum summed completeness by approximately **5%**. This value will be highly dependent on mission parameters

We gratefully acknowledge support for this work under the JPL SURP program.