The utility of astrometry as a precursor to direct detection

SPIE Optical Engineering + Applications

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Motivation

- If the frequency of exoplanets is low, direct detection planet finding missions may fail.
- It has been suggested that precursor missions may be necessary for the success of a direct detection mission.
- We need to quantify the effects of precursor knowledge on the science yield of a direct detection mission, and find any requirements on the accuracy of such data.

ExoPTF Report states that...

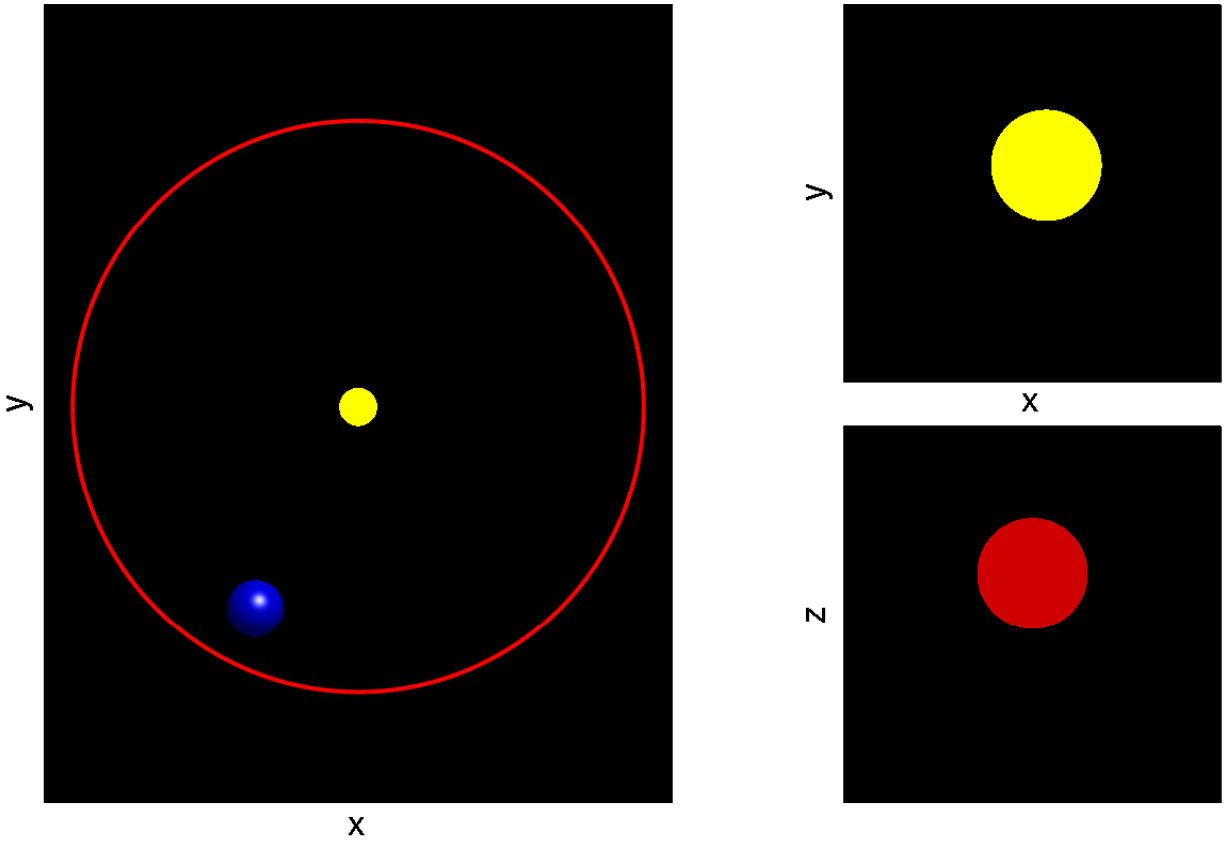
"...the locations and times of maximum star-planet angular separations determined by an astrometric mission [would] make the follow on direct detection planet characterization missions more cost-effective and observationally efficient." [Lunine et al., 2008]

Outline

Direct Detection and Some Possible Precursors

- Direct Detection
  - Observe planet position with respect to star in the plane of the sky, and planet's brightness (magnitude) at time of observation.
  - Limiting Δmag - maximum achievable difference in brightness between planet and star.
  - Inner working angle (IWA) - minimum angular separation between a target and the line of sight.
- Precursors
  - Astrometry - Observe position of star in plane of the sky with respect to centroid determined by group of reference stars.
  - Radial Velocity - Observe velocity of star along line of sight.

System Dynamics



Observation of Earth-twin. (a) Direct detection view. (b) Astrometry view. (c) Radial velocity view.

Observations

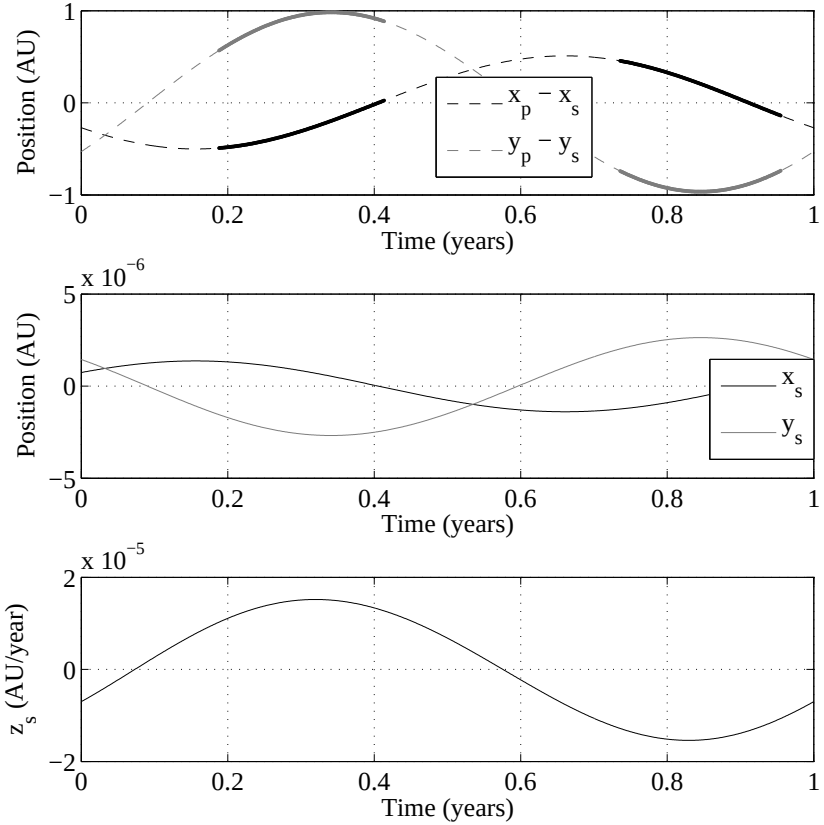


Figure: Observed data from planetary system. (a) Direct detection. (b) Astrometry. (c) Radial velocity.

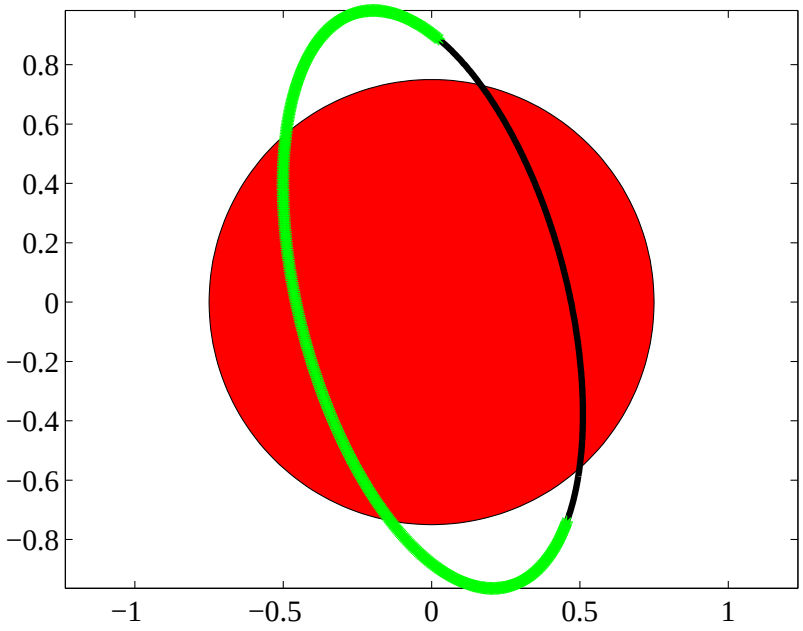


Figure: Schematic of a planetary system. Red circle represents projected IWA. Planet is sufficiently illuminated on green portion of the orbit.

Unhelpful Precursor Data

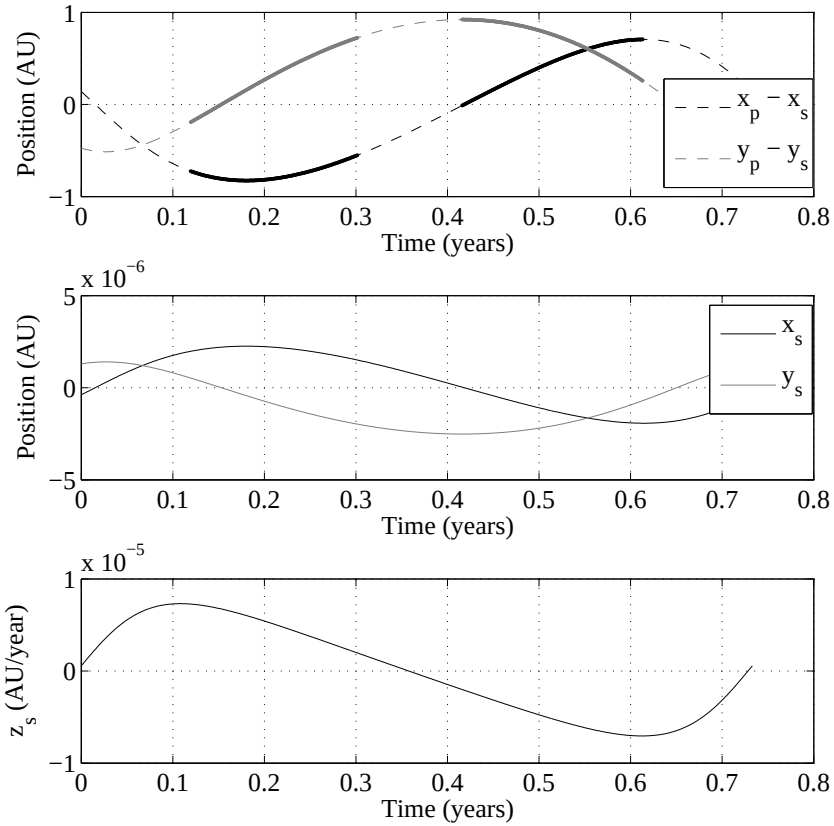


Figure: Earth-twin on a 0.8 AU semi-major axis, 0.3 eccentricity orbit: (a) Components of apparent separation. (b) Components of star's position with respect to system barycenter, in the plane of the sky. (c) Radial velocity of the star.

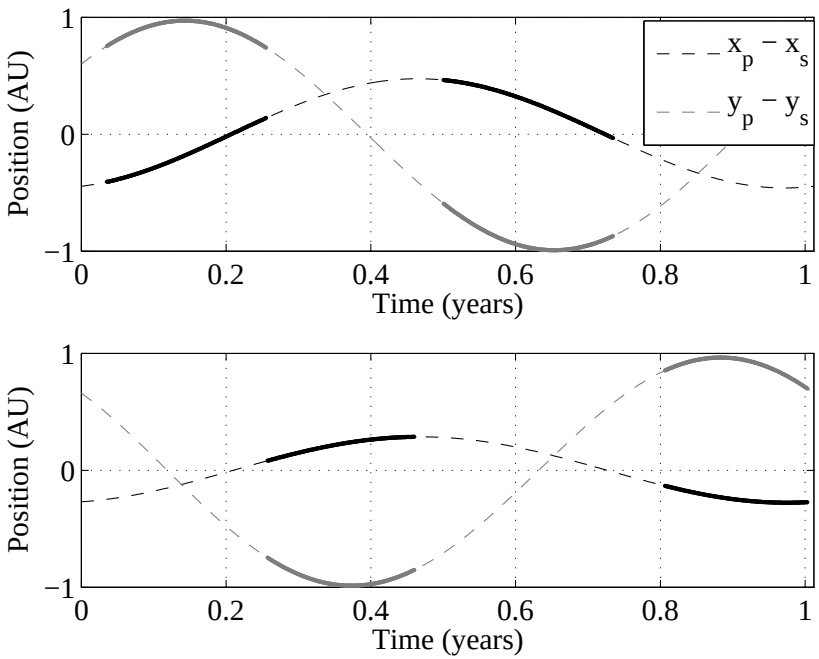


Figure: Earth-twin on a 1 AU semi-major axis and 0.0167 eccentricity orbit, the components of apparent separation for: (a) The original planet position propagated forward by five years. (b) The planet position derived from average orbital elements with an initial 0.1% error in the semi-major axis.

Outline

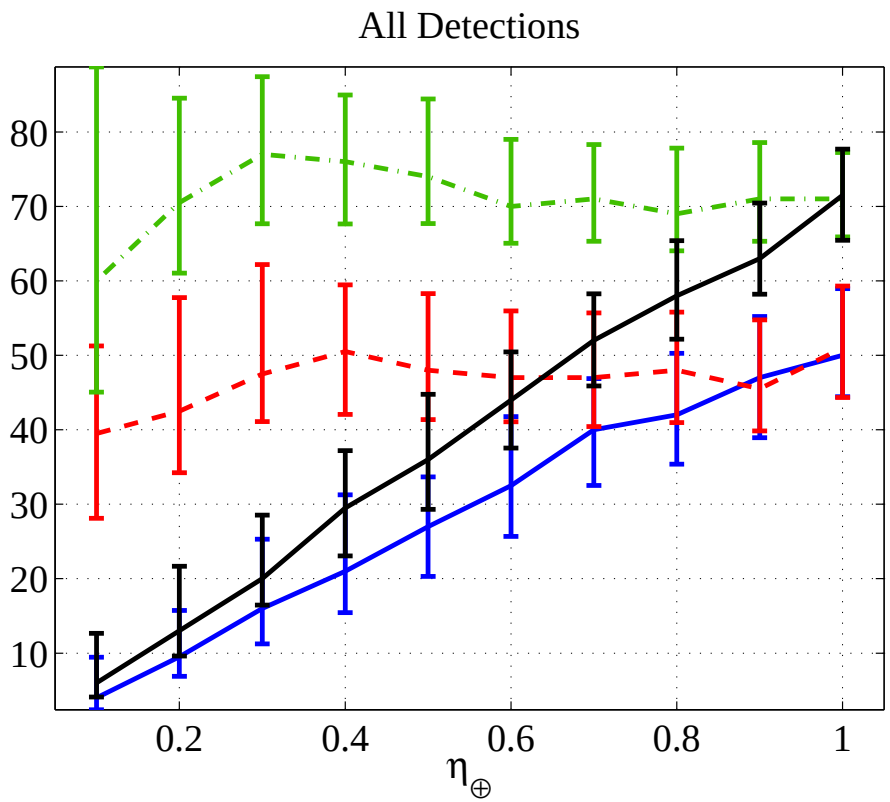
Mission Simulation

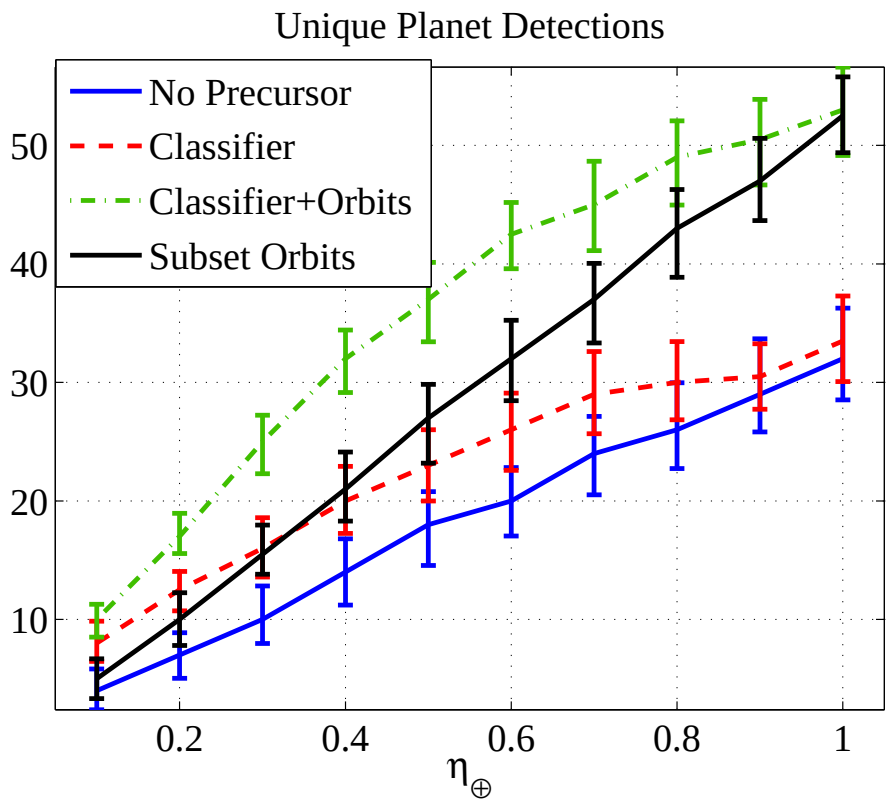
- Simulate complete missions with randomly generated populations of planets. [Savransky and Kasdin, 2008]
- Generate ensembles of mission timelines and derive key science yield metrics:
  - All Detections
  - Unique Detections
  - Unique Targets
  - Spectral Characterizations
- Use THEIA mission concept as the direct detection planet finder on a universe of Earth-twins in the habitable zone. [Spergel et al., 2009]

Precursor data incorporated into scheduling algorithm as

- Classifiers - Know which stars have planets.
- Orbit Fitters - Precursor produces orbital elements for discovered planets.

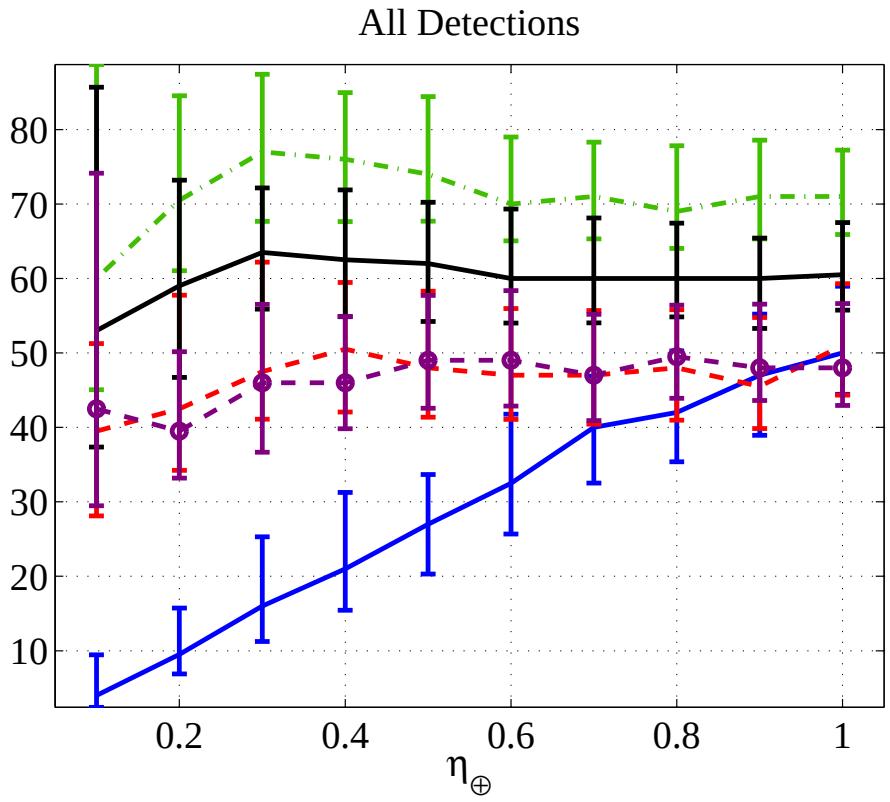
Ideal Cases

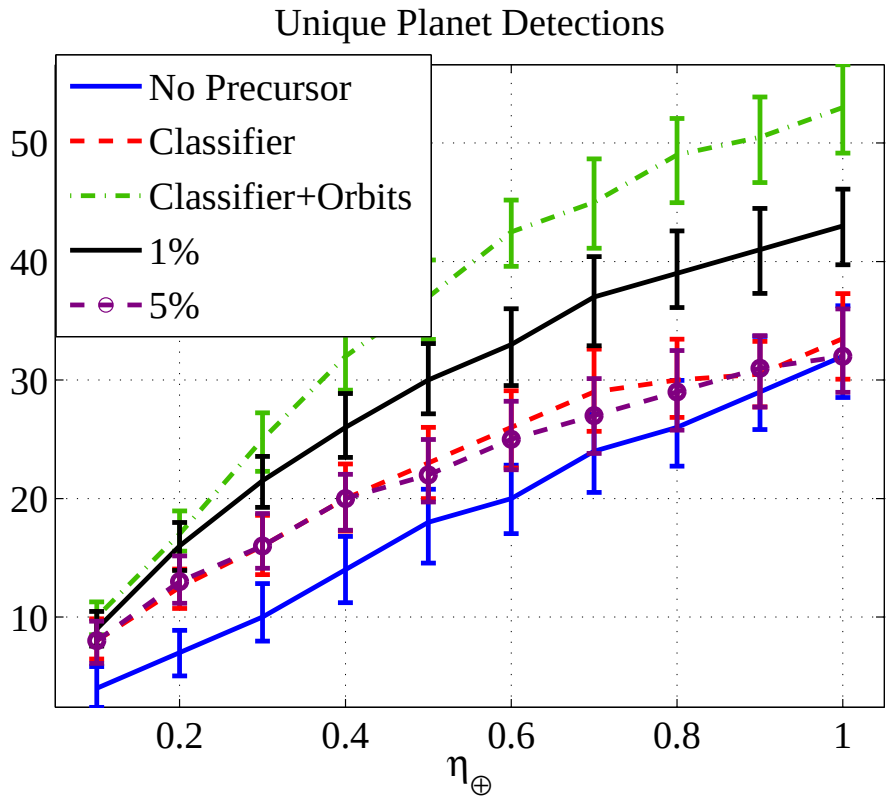




- Perfect orbital knowledge increases number of planets found from 30% to 50% of all existing planets in simulation.
- Classifier knowledge by itself is helpful for other science in low $\eta_\oplus$ cases, but only helps find a small number of additional planets.

Non-Ideal Cases





- 1% and 5% cases are precursors modeled as ideal classifiers which produce orbital fits with 0.1% errors in the semi-major axis estimate, and errors in the eccentricity and orbit inclination of 1% and 5% each.
- At 1% error, 15% fewer unique detections are made.
- At 5% error, the precursor produces results identical to the ideal classifier only (no benefit from orbital data).

Conclusions

- Classification alone does not significantly improve the science yield of a direct detection mission, although it provides more observing time for other instruments in low η cases.
- Perfect orbital knowledge significantly improves science yield, if planetary radii and albedo are also known (or can be constrained).
- Small errors (as low as 1% in period and 5% in eccentricity and inclination) make orbital data useless for planning detections.
- The precursor knowledge modeled here is actually quite optimistic - ideal classifiers are unrealistic and the assumed errors in orbital knowledge are quite low. [Brown, 2009]
- While many of the proposed precursor instruments have other, very good scientific justifications, it has not yet been demonstrated that these include their ability to improve the efficiency or yield of direct detection missions.

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System Formulation

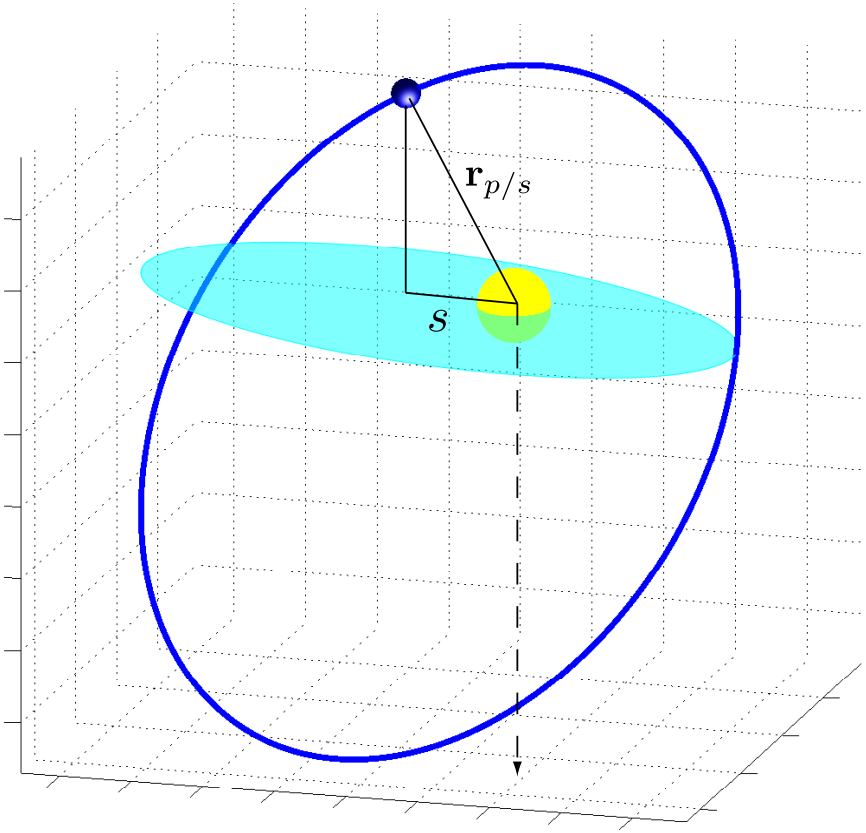
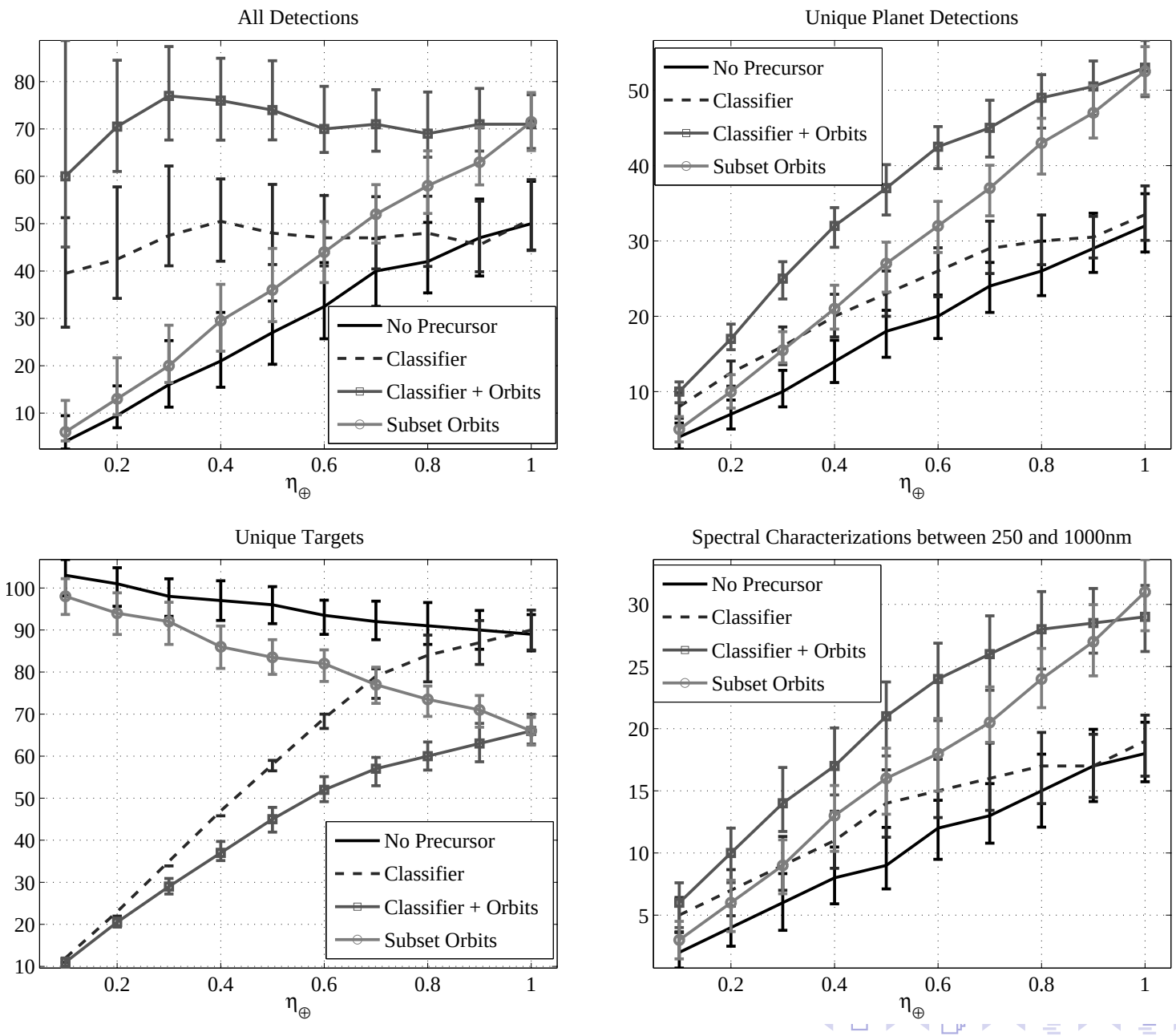


Figure: Schematic of a planetary system.

- Coordinate system defined with origin at barycenter, with $\hat{\mathbf{z}}$ unit vector parallel to line of sight.
- $\mathbf{r}_p$ and $\mathbf{r}_s$ are the positions of a planet and star with respect to the barycenter of the planetary system, with components (x_p, y_p, z_p) and (x_s, y_s, z_s), respectively.
- $\mathbf{r}_{p/s} = \mathbf{r}_p - \mathbf{r}_s$ is the position of the planet with respect to the star.
- Direct detection produces values for $(x_p - x_s, y_p - y_s)$.
  $s = \|(x_p - x_s, y_p - y_s)\|$.
- Astrometry produces values for (x_s, y_s).
- Radial velocity produces values for $\dot{z}_s$.

Ideal Cases


All Detections
Unique Planet Detections
Unique Targets
Spectral Characterizations between 250 and 1000nm
No Precursor
Classifier
Classifier + Orbits
Subset Orbits
$\eta_\oplus$

Non-Ideal Cases