How orbital fit uncertainties impact dynamic scheduling

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Introduction

To increase the number of detections future direct imaging missions are planning to observe many planets that have been observed by radial velocity (RV) instruments already. Planets known based on RV measurements will have orbital fits of varying accuracy depending on the measurement error. Current state of the art can observe with a precision of approximately 1 m/s on RV measurements. To fit a terrestrial planet the RV precision needs to be improved because the RV signiatures are only tens of centimeters in amplitude. As the precision increases orbital fits will improve, but a radial velocity fit cannot provide all of the keplerian parameters necessary to simulate an observation. Here we examine the cost of poor orbital fits on scheduling direct imaging observations.

Fitting the RV curve

- To fit orbital parameters to the RV data we use the python package RadVel [1] which uses Markov Chain Monte Carlo (MCMC)
- For the fit we created Gaussian priors for the period (T) and time of conjunction (T_p)

The fitted parameters

RadVel fitting basis

$$T_c, T, K, \sqrt{e}\sin\omega_s, \sqrt{e}\cos\omega_s$$

- Where T_c is the time of inferior conjunction, T is the period, K is the semi-amplitude, and ω_s is the star's argument of periastron
- The following equations are used to solve for the standard Keplerian parameters

Solved parameter	From RV fit	Equations
Semi-major axis, a	T	$a = \left(GM_s\left(\frac{T}{2\pi}\right)\right)^{\frac{1}{3}}$
Eccentricity, e	$\sqrt{e}\cos\omega_s, \sqrt{e}\sin\omega_s$	$e = (\sqrt{e}\cos(\omega_s))^2 + (\sqrt{e}\sin(\omega_s))^2$
Planet's argument of periastron, ω_p	$\sqrt{e}\cos\omega_s, \sqrt{e}\sin\omega_s$	$\omega_s = \arctan\left(\frac{\sqrt{e}\sin(\omega_s)}{\sqrt{e}\cos(\omega_s)}\right)$ $\omega_p = \omega_s + \pi$
Time of periastron, T_p	T, e, ω_s, T_c	$\nu_p = \pi/2 - \omega_s$ $\tan\left(\frac{E}{2}\right) = \sqrt{\frac{1-e}{1+e}}\tan\left(\frac{\nu}{2}\right)$ $M = E - e\sin E$ $T_p = T_c - \frac{MT}{2\pi}$
$M_p \sin i$	K, T, e	$M_p\sin i = \left(\frac{T}{2\pi G}\right)^{\frac{1}{3}} K M_s^{\frac{2}{3}}\sqrt{1-e^2}$

- With only RV data the inclination and mass cannot be separated and the planet's radius cannot be determined
- Therefore, to estimate when the planet will be visible we need to sample those parameters separately

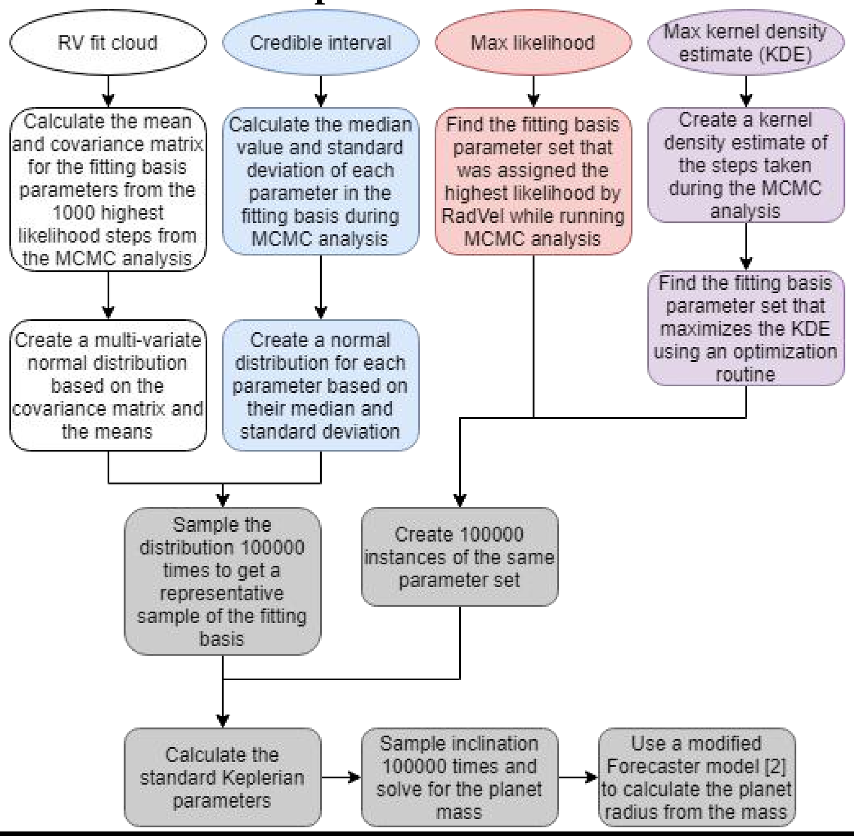
Estimating probability of detection

- Our goal is to estimate when a planet will be visible to an observatory, or when the planet is within the observatory's field of view and bright enough.

$$\text{Probability of detection} = \frac{\text{Number of currently visible planets in population}}{\text{Number of planets in population}}$$

- The visibility was based off of HabEx [3]

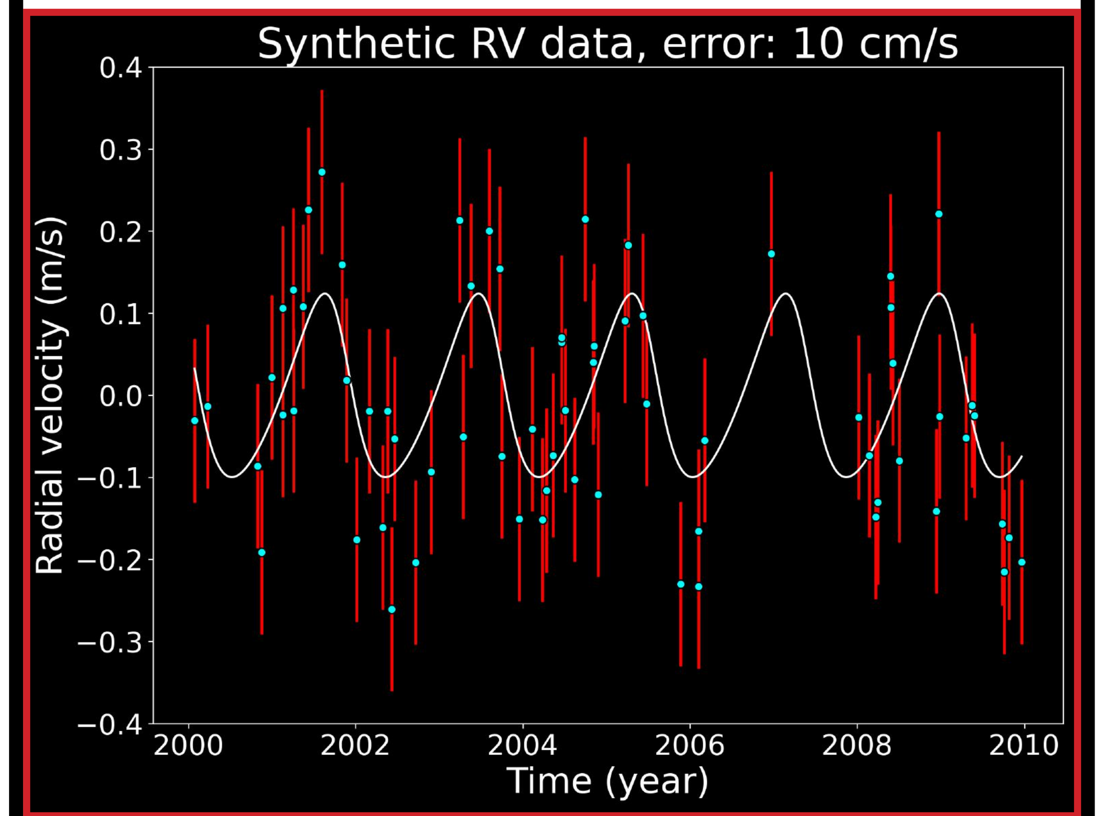
Population definitions

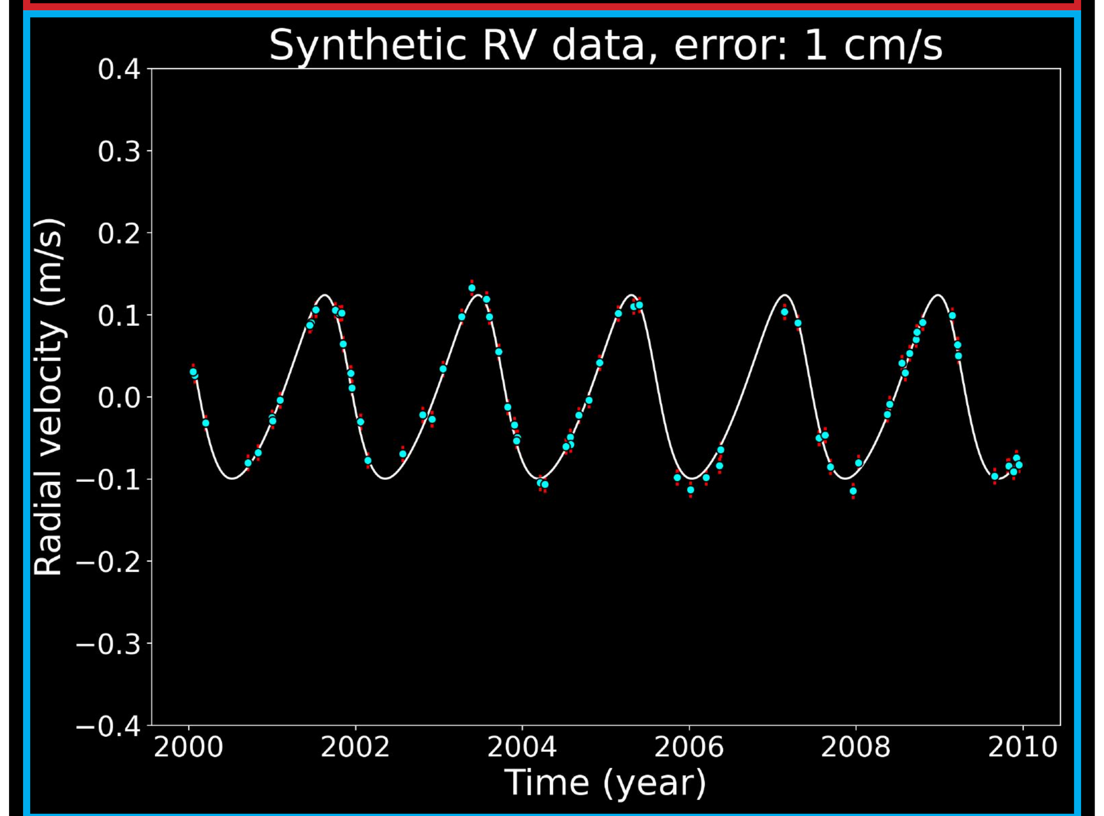


Synthetic RV data

- The RV plots shown below were created using on the following superearth parameters

Parameter	Value	Unit
Semi-major axis a	1.5	AU
Eccentricity e	0.198	
Inclination i	90	Degrees
Planet mass M_p	1.5	$M_\oplus$
Planet radius R_p	1.12	$R_\oplus$
Argument of periastron ω_p	4.14	Radians
Distance from observer d	10	Parsecs
Star mass M_s	1	$M_\odot$



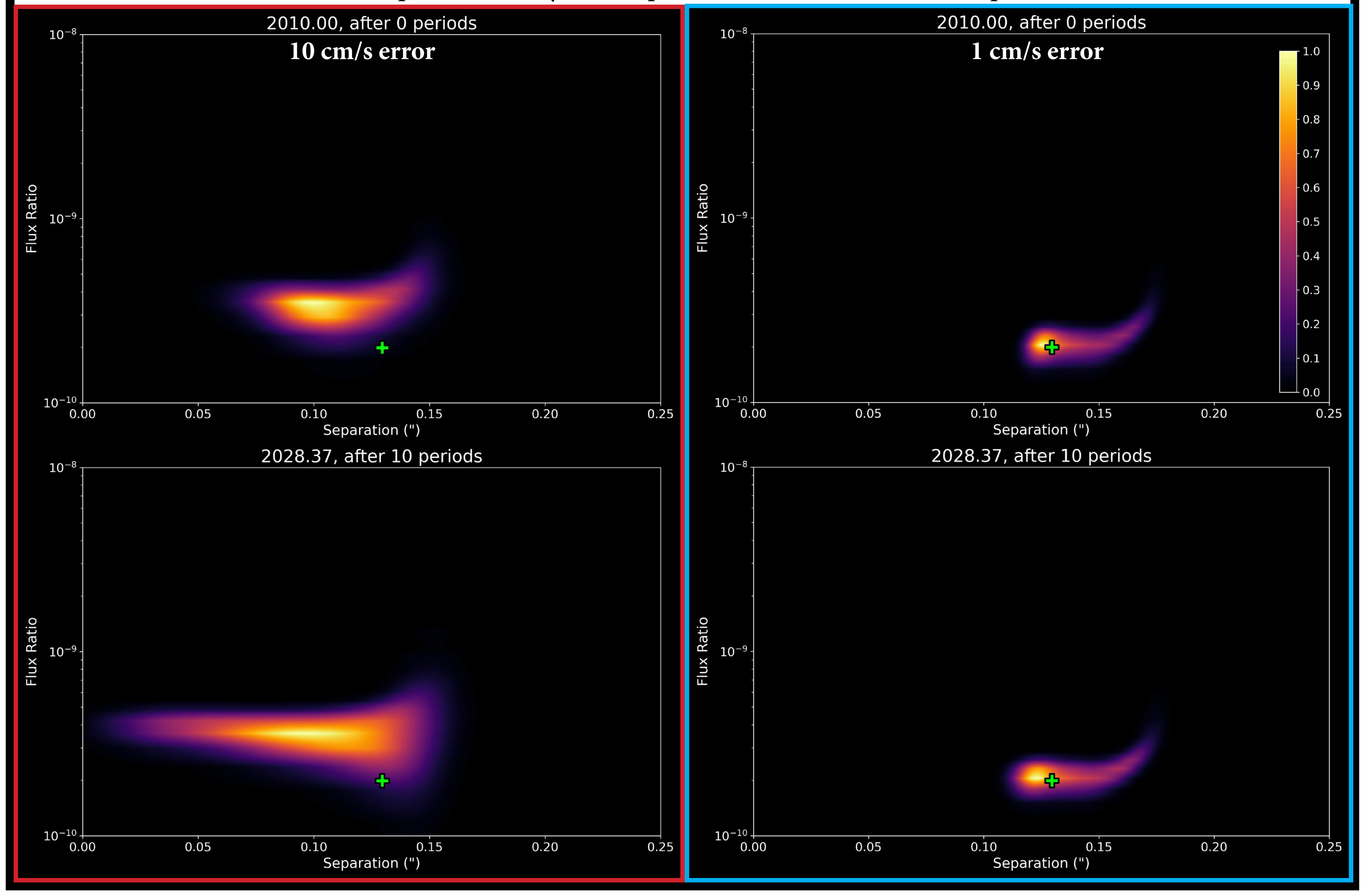


- These plots shows the true radial velocity of the synthetic planet as a white line and the simulated observations as blue points.

How RV fits spread out visually

These plots show how the "RV fit cloud" population disperses in time in the flux ratio (ratio of planet brightness to star brightness) vs separation (angular distance between the star and planet) space

The star represents the synthetic planet's actual flux ratio and separation



Conclusions

- With 1 cm/s RV error the orbital fit of a super-Earth can be reliably estimated for over 20 years.
- With 10 cm/s RV error the the orbital fit of a super-Earth degrades within 10 years and may immediately overestimate the probability of detection.
- Using a single parameters set (max likelihood/KDE) to estimate a planet's orbital elements can give 100% probability of detection when the planet is not visible.
- Creating populations based on fitted parameter distributions (RV fit cloud, credible interval) degrades faster but do not provide false confidence

References

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[2] D. Savransky, C. Gascon, N. Kinzly, N. Batalha, N. Lewis, and M. Marley, "Exploration of the dynamical phase space of stars with known planets," in Techniques and Instrumentation for Detection of ExoplanetsIX, S. B. Shaklan, ed.,11117, p. 51, SPIE, sep 2019.
[3] "The Habitable Exoplanet Observatory (HabEx) Mission Concept Study Final Report," 2020.

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