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Simulating *Roman* Astrometry of Terra Hunting Stars

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ABSTRACT

The *Nancy Grace Roman Space Telescope*, scheduled to launch in late 2025, will be capable of precision astrometry using its wide field imager. For bright stars, *Roman* may be able to achieve astrometric accuracy of 1-10 as. We have simulated an observing program that combines *Roman* astrometry observations with radial velocity measurements. Astrometry and radial velocity measurements are complementary: radial velocity measurements are most sensitive to planets close to its host star, while the astrometric signal is largest for more distant planets. Astrometric measurements can also break the mass-inclination degeneracy in radial velocity observations. Our simulations are based on the observing program of the Terra Hunting Experiment, which will take nightly Doppler radial velocity observations (starting in 2022) of Sun-like stars in search of planets that are Earth-like in mass and temperature. We also discuss how *Roman* astrometry could lead to the discovery of companion planets not directly detectable from radial velocity observations alone.

1. INTRODUCTION

1.1. *Exoplanet Astrometry*

- Four of the major goals of exoplanet astrometry, as described in EXOPLANETS TEXTBOOK NEED CITATION are:

  1. Mass determination for planets detected in radial velocity surveys (without the sin i factor). With astrometry we can determine the precise mass for non-transiting planets, rather than just a mass lower limit.
  2. Search for long-period planets around nearby stars of all spectral types. The astrometric precision is independent of spectral type (although we are biased by our stellar mass determination).
  3. Determine whether multiple systems are coplanar or not. This is interesting the the context of stability, formation, and thinking about planetary systems that mimic the solar system.
  4. Search for terrestrial planets orbiting stars in the solar neighborhood. They argue that you require a precision of 0.3 μas, which assumes a distance to the star of 10pc. How many sun-like stars are there in this solar neighborhood ($< 10pc$ from the Sun)? See Figure 1.2.

1.2. *Nancy Grace Roman Space Telescope*

- *Roman* will provide at least a factor of three improvement in astrometry over the current state of the art in this wavelength range, while spanning a field of view thousands of times larger." For exoplanet detection, you want to look nearby (< 10 pc). A dedicated GO program with a flexible observing schedule to go after the most promising targets would be important for this effort.(1)

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- "*Roman* could detect Earth-mass exoplanets astrometrically around the most nearby stars, in some cases even in their respective habitable zones. In addition, it can probe Neptune-class planets around more distant stars and, by adding earlier measurements from Gaia, rocky planets with periods of >10 yr. Such measurements would be strongly synergistic with radial velocity campaigns, improving the mass constraints and breaking degeneracies in several orbital parameters, and enabling mass estimates of the direct-imaging exoplanets of the *Roman* coronagraph and possible starshade occulter programs." (1)

- **Diffraction Spikes Method** We could obtain 10 μas astrometric observations with single 100s exposures for a R=6 or J=5 star. Further, this precision astrometric detection would be enough to detect Earth-mass exoplanets around stars within a few pc with orbital periods $\geq$ 1 year – with a dedicated *Roman* GO program to this endeavor. (2)

- **Spatial Scanning Method** The spatial scanning method has been used to observe bright Cepheids with astrometric precision of 20-40 μas with *Hubble* (3)

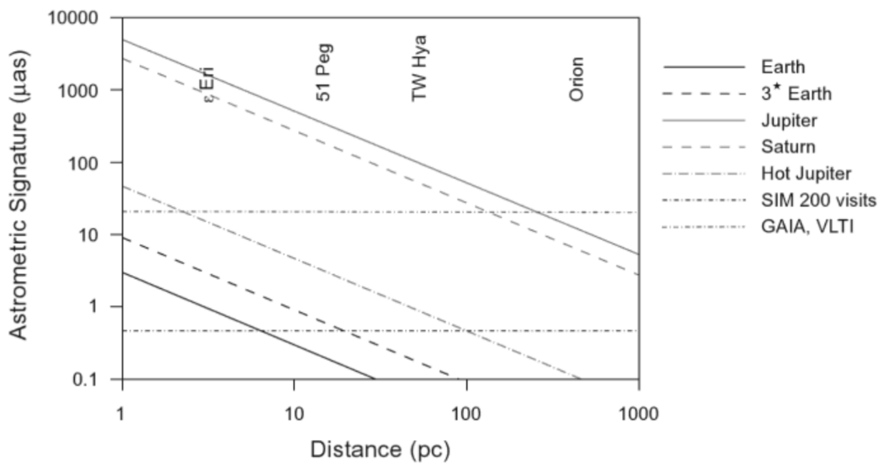


Fig. 1. Astrometric signature (semiamplitude) for five sample planets orbiting a solar-mass star, as a function of distance. Anticipated detection limits for Gaia, VLTI, and the Space Interferometry Mission are also shown. The vertical arrows mark the distances of benchmark objects in the solar neighborhood.

1.3. *Terra Hunting Experiment*

1.4. *Methods*

- **SPOCK** The SPOCK code uses N-body simulations for 10^4 orbits of the inner planet and then uses machine learning on training data from the original 10^4 N-body orbits to simulate out to 10^9 orbits. As the machine learning code runs almost instantaneously, it can speed up simulations by up to 10^5 times vs. 10^9 N-body orbit simulations. Computational time is a big limiting factor in these traditional N-body models. The paper then describes three other analytical methods that have been used to study stability, showing that the SPOCK method provides better constraints on stability than the other methods (Hill radius analysis, AMD method, and MEGNO (chaos indicator)). The SPOCK method focuses on the limit of closely separated planets, as there is a strong observational bias in detecting planets close to their host star resulting in a bias to compact populations of multiplanet systems. (4)

- **SPOCK on Kepler-23** SPOCK was run on Kepler 23. In this tightly packed system, stability (with SPOCK) can place upper limits on the masses and orbital eccentricities of the bodies that are comparable to current state of the art TTV values and tighter than TDV values. For the sample of Kepler-23 configurations, the SPOCK stability estimates deviate from the full N-body simulations by $< 20\%$. Given this, stability is particularly a strong method to be used in systems observed over short time baselines where TTVs rarely provide strong constraints. This is relevant for Roman astrometry of Terra Hunting targets, where we will be going after long period targets.

1.5. *Equations*

Adapted from...

- Mede and Brandt, 2017 (ExoSOFT)
- Exoplanet Textbook, Astrometry Section (Page 160-161):

Radial velocity equations

$$v(t) = K_1\Big(\cos[\theta(t) + \omega_1] + e\cos(\omega_1)\Big) + \gamma$$

where,

$$K_1 = [\frac{2\pi G}{P}]^{\frac{1}{3}} \frac{m_2 \ \sin i}{m_{tot}^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}$$

For a circular orbit, e = 0 so this reduces to:

$$K_1 = [\frac{2\pi G}{P}]^{\frac{1}{3}} \frac{m_2 \ \mathrm{sin}i}{m_{tot}^{\frac{2}{3}}}$$

Kepler's Third Law (where a_{tot} is the semi-major axis and m_{tot} is the total mass, or for a single planet system $m_{tot} = m_1 + m_2$):

$$a_{tot} = [\frac{P^2 \, G \, m_{tot}}{4\pi^2}]^{\frac{1}{3}}$$

For a circular orbit, $a_{tot} = R$, so this becomes:

$$R = [\frac{P^2 \, G \, m_{tot}}{4\pi^2}]^{\frac{1}{3}}$$

Astrometric observation equations

$$\xi(t) = \alpha_0^\star + P_{\alpha^\star}\bar{\omega} + (t - t_0)\mu_{\alpha^\star} + BX(t) + GY(t)$$

$$\eta(t) = \delta_0 + P_\delta\bar{\omega} + (t - t_0)\mu_\delta + AX(t) + FY(t)$$

where,

$$X(t) = cos(E(t)) - e$$

$$Y(t) = \sqrt{1-e^2}\sin(E(t))$$

where E is the eccentric anomaly, the solution to the Kepler's equation...

$$E = \frac{2P}{\pi}(t - T) + e\sin E$$

parametrized with the Thiele–Innes method:

$$A = \theta(\cos\Omega_2\cos\omega_2 - \sin\Omega_2\sin\omega_2\cos i)$$

$$B = \theta(\sin\Omega_2\cos\omega_2 + \cos\Omega_2\sin\omega_2\cos i)$$

$$F = \theta(-\cos\Omega_2\sin\omega_2 - \sin\Omega_2\cos\omega_2\cos i)$$

$$G = \theta(-\sin\Omega_2\sin\omega_2 + \cos\Omega_2\cos\omega_2\cos i)$$

In the above equations, θ is the astrometric signal of a planet. If we take the mass of the planet to be "$\mathrm{m_p}$" orbiting a star with mass "$\mathrm{m_\star}$" and assume a circular orbit and that $\mathrm{m_p} \ll \mathrm{m_\star}$. At a distance "d" from the observer and a radius "a," the astrometric signal, θ equals...

$$\theta = \frac{\mathrm{m_p}}{\mathrm{m_\star}}\frac{\mathrm{a}}{\mathrm{d}} = \left(\frac{\mathrm{G}}{4\pi^2}\right)^{1/3}\frac{\mathrm{m_p}}{\mathrm{m_\star^{2/3}}}\frac{\mathrm{P^{2/3}}}{\mathrm{d}}$$

$$\theta = 3\,\mu\mathrm{as}\cdot\left(\frac{\mathrm{m_p}}{\mathrm{M_\oplus}}\right)\left(\frac{\mathrm{m_\star}}{\mathrm{M_\odot}}\right)^{-2/3}\left(\frac{\mathrm{P}}{\mathrm{yr}}\right)^{2/3}\left(\frac{\mathrm{d}}{\mathrm{pc}}\right)^{-1}$$

Process

The equations in this section above a set of observables (v, $\Delta\alpha$, and $\Delta\delta$), based on a set of parameters, that we then compare to the corresponding measurements.

We can best fit for these parameters using an MCMC model. Or we could adopt previously written code like ExoSOFT. Or if this is more just to get a first level understanding, I could play around with different values and just see what the orbits looks like?

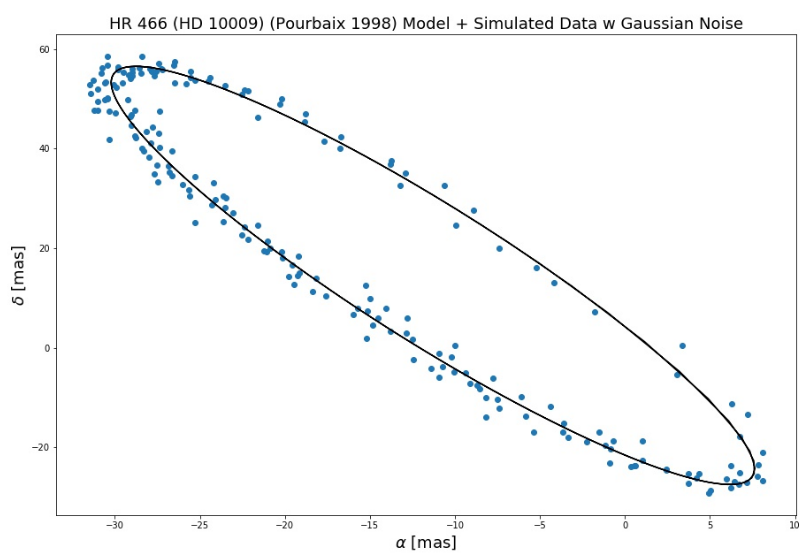
In writing our our least squares fit, we will have a 12-parameter model. This can be generalized to multiple systems, fully described by 7n + 5 parameters for n systems. Assuming that the gravitational interactions between the planets can be neglected.

2. *ROMAN* ASTROMETRY OF PLANET-NAME RADIAL VELOCITY OBSERVATIONS

3. EXOPLANET CLASSIFICATION WITH *ROMAN* AND TERRA HUNTING

3.1. *Exoplanet Detectability*

3.2. *The single planet case*

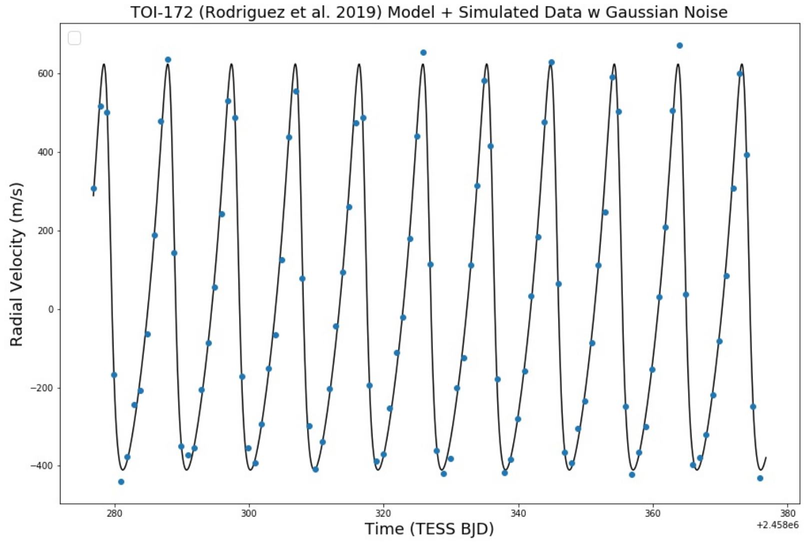


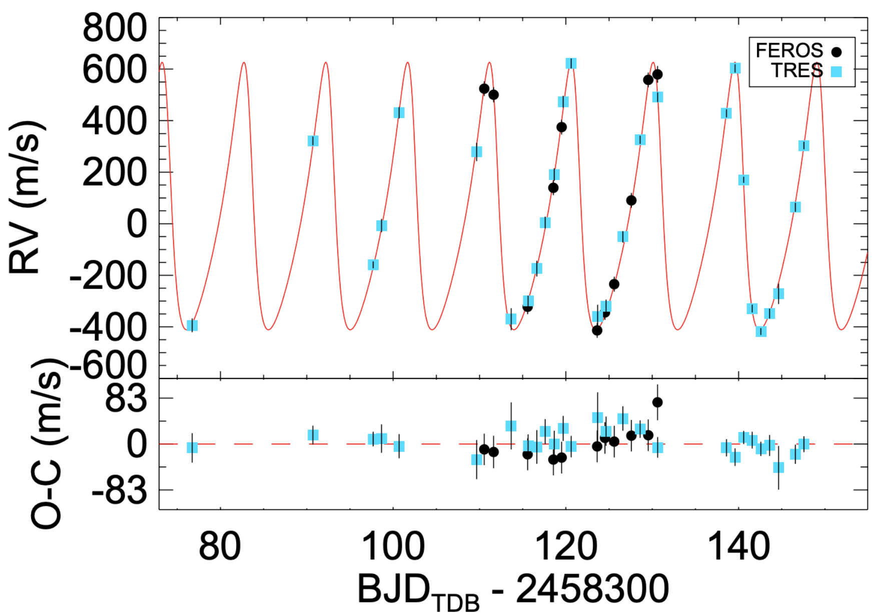
3.3. *The multi-planet case*

4. DISCUSSION

4.1. *Future Work*

5. CONCLUSION





Software:

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