Joint Radial Velocity and Direct Imaging Planet Yield Calculations II

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Abstract

The future flagship direct imaging mission Habitable Worlds Observatory aims to catalog and characterize Earth-mass analogs around nearby Sun-like stars. The exoplanet yield of these missions will be strongly dependent on the frequency of Earth-mass planets, and the survey efficiency is dependent upon the a priori knowledge of which stars specifically host suitable planetary systems. Ground or space based radial velocity surveys could potentially perform the pre-selection of targets and observation times. We present the second in a series of papers simulating future precise radial velocity surveys of nearby direct imaging targets. In this paper, we expand on our framework for: simulating a schedule of observations for a given observatory, spectrograph, and target list; generating a radial velocity time series given an observational time series; and calculating exposure times for a target single measurement precision. We consider multiple representative telescope apertures, including their location, weather conditions, observation time limitations, and instrument sensitivities. From this, we generate realistic measurement frequencies, qualities, and achieved RV precision and sensitivity. We find that the resulting number of observations per star and thus exoplanet sensitivity can be sensitive to the target right ascension distribution and density on the sky, depending on the desired RV precision, telescope aperture and thus resulting target dwell times. The simulated observation cadences herein can both be refined in the future to further improve the fidelity and realism, as well as be used for injection and recovery tests in the presence of stellar activity to assess the success of the radial velocity technique to identify candidate Earth-mass planets for future flagship direct imaging.

We also implement exposure times correcting for realistic stellar p-mode oscillations, and find them to have little effect on observation time requirements and survey sensitivity. We also consider uncorrected telluric noise, concluding that it has minimal effect in visible light, though dominates over other effects in near infrared.

Survey Targets and Architectures

We use the survey code described in Newman et al (2023).

We directly use the ExEP list of stars by Mamajek and Stapelfeldt (2024), containing 164 nearby stars (mostly FGK, all low stellar activity) that are likely targets for HWO (Habitable Worlds Observatory). We do not perform any additional cuts in terms of declination, spectral type, etc.

We simulate 3 telescopes (nominally 4, 8, and 12 m class) based off of existing systems. We also simulate two representative spectrographs (one visible and one near-IR). A number of target single measurement precisions are used (40 cm/s, 27 cm/s, 9 cm/s, and 3 cm/s). While we do simulate all possible telescope/instrument/precision combinations, outside of confirming our p-mode and telluric models, we only focus on more representative ones:

Telescope	Diameter (m)	Instrument	Wavelength Range (Å)	Nominal Precision (cm/s)
WIYN	3.5	NEID	3800 - 9300	27
LBT	8.4x2	NIRS	9700 - 13000	40
WIYN	3.5	Super NEID	3800 - 9300	3
LBT	8.4x2	Super NEID	3800 - 9300	3
LBT	8.4x2	Super NIRS	9700 - 13000	3

Table: The primary ("canonical") telescope and spectrograph combinations considered. While specific telescopes are listed, these are nominal ones chosen as representative 4/8/12 m class observatories. The collecting area of the 2x8.4 m is simulated as a single 11.78 m telescope.

The 3.5 m telescope is sited at Kitt Peak and the 8.4 m / 11.8 m telescopes are sited at Mount Graham.

Selected Results

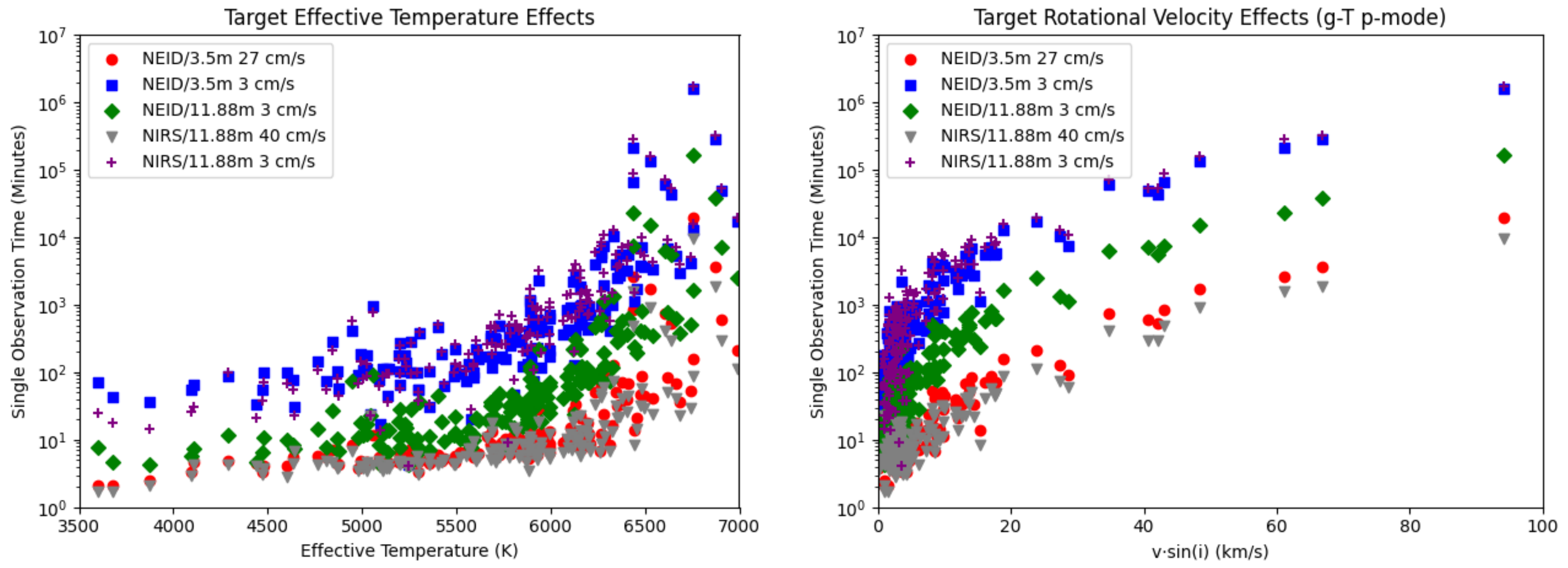

Figure: Exposure times as functions of effective temperature and v·sin(i). These are for the variable p-mode (modeled using surface gravity and effective temperature) case.

P-mode Compensation

We look at fixed 5-minute and 10-minute exposure time minimums, as well as two ways of scaling based off of the properties of the star:

$$T_{min} = 300\sqrt{\frac{(R/R_{\odot})^3}{M/M_{\odot}}} \tag{1}$$

$$\nu_{max} = 3100\mu Hz \left(\frac{g}{g_{\odot}}\right)^1 \left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{-0.5} \tag{2}$$

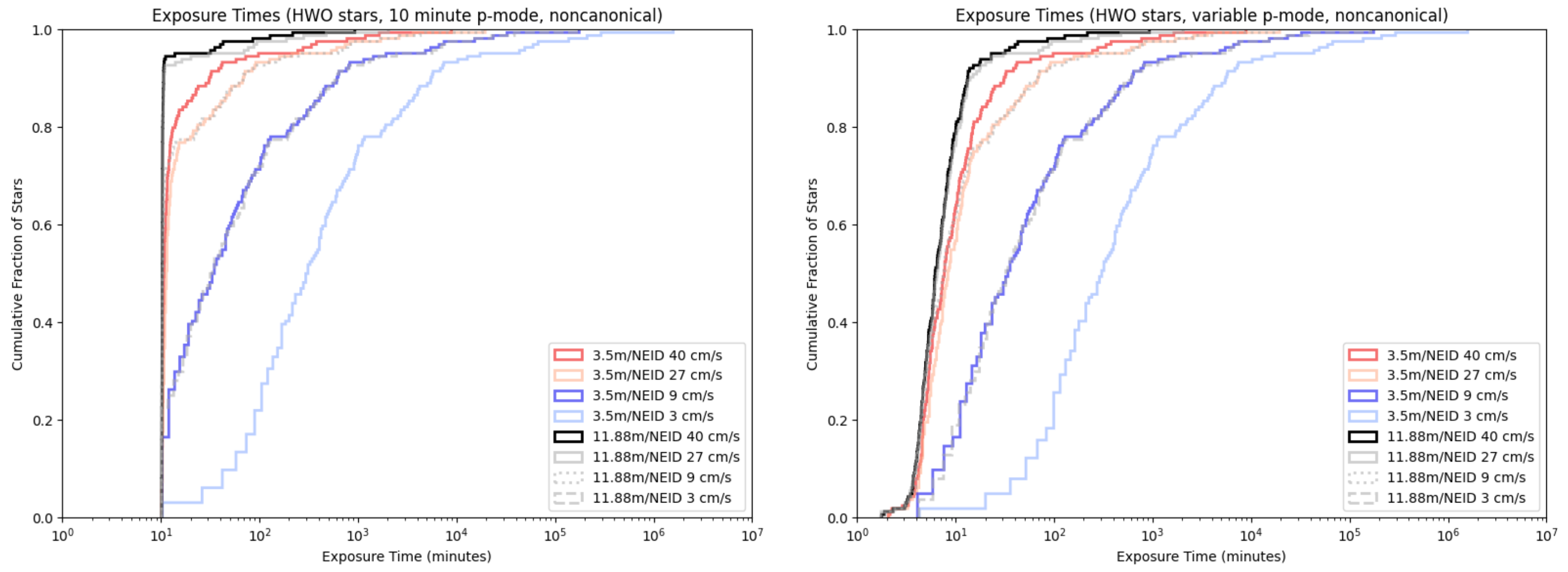

Figure: Exposure times for all star/instrument/telescope combinations using different p-mode compensation.

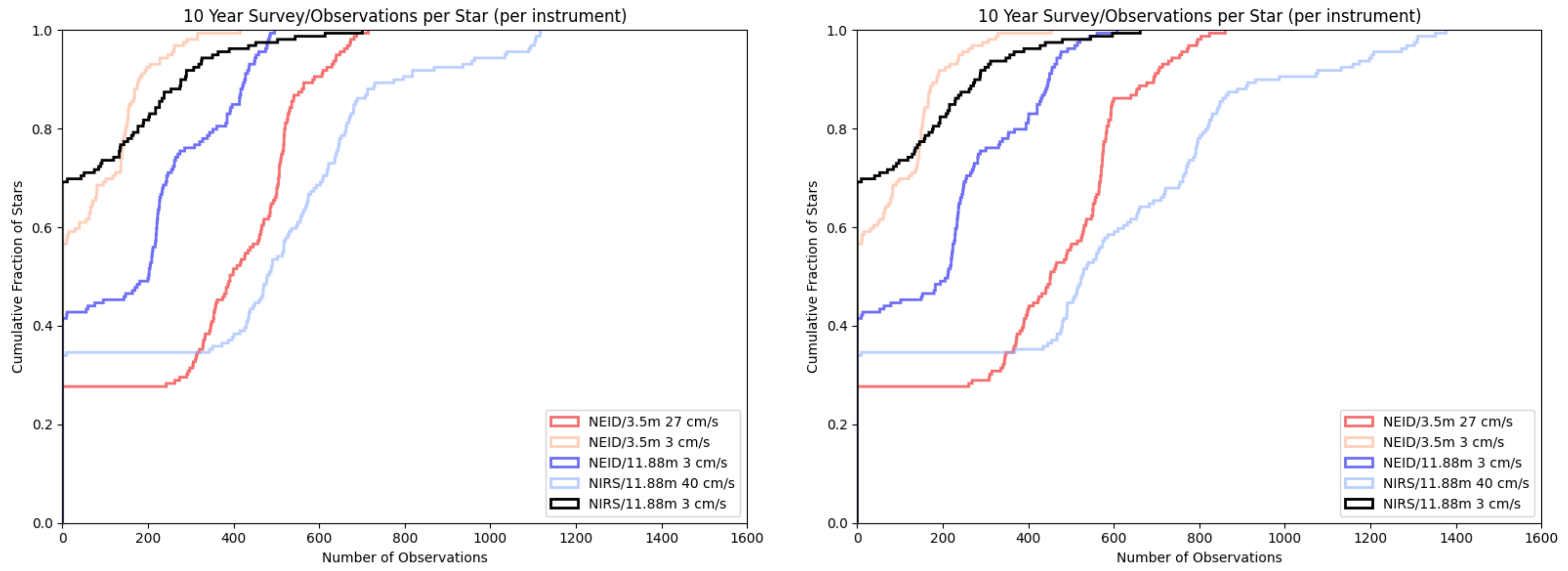

Figure: Observation counts for all star/instrument/telescope combinations using different p-mode compensation.

Planet Recovery (Figure of Merit)

To avoid compute-intensive injection and recovery tests, we use a figure of merit that assumes a planet of arbitrary mass and (aside from being much shorter than the survey duration unknown arbitrary period) in a circular orbit around the star. (Gaudi and Winn 2007)

$$SNR = \frac{K}{\sqrt{2}}\sqrt{\frac{N_{\mathrm{obs}}}{\sigma^2}} \tag{3}$$

Since we consider σ as a sum of all noise terms (photon noise, detector noise, telluric noise, etc.), this is actually a composite value that can vary between observations. Both SNR for a potential k = 10 cm/s, and k for an SNR = 10 detection are considered for all architectures.

Selected Results

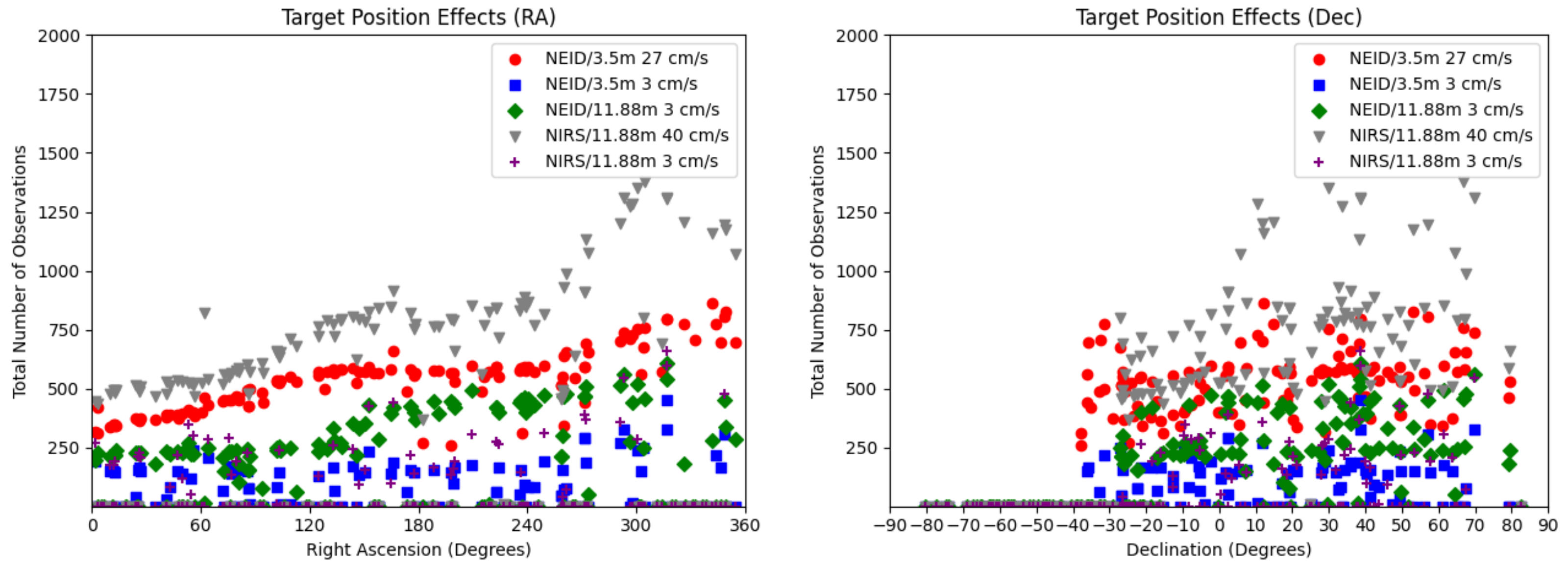

Figure: Observation counts as functions of RA and Dec.

Planet Recovery (Telluric Noise)

We consider: no tellurics (0 cm/s), and uncorrected noise of: 3 cm/s in the visible visible and / 115 cm/s in the NIR. These amounts of noise are manageable in the visible (being smaller than other sources in all but our most optimistic simulations), while they completely derail the infrared observations (due to being larger than any other noise source).

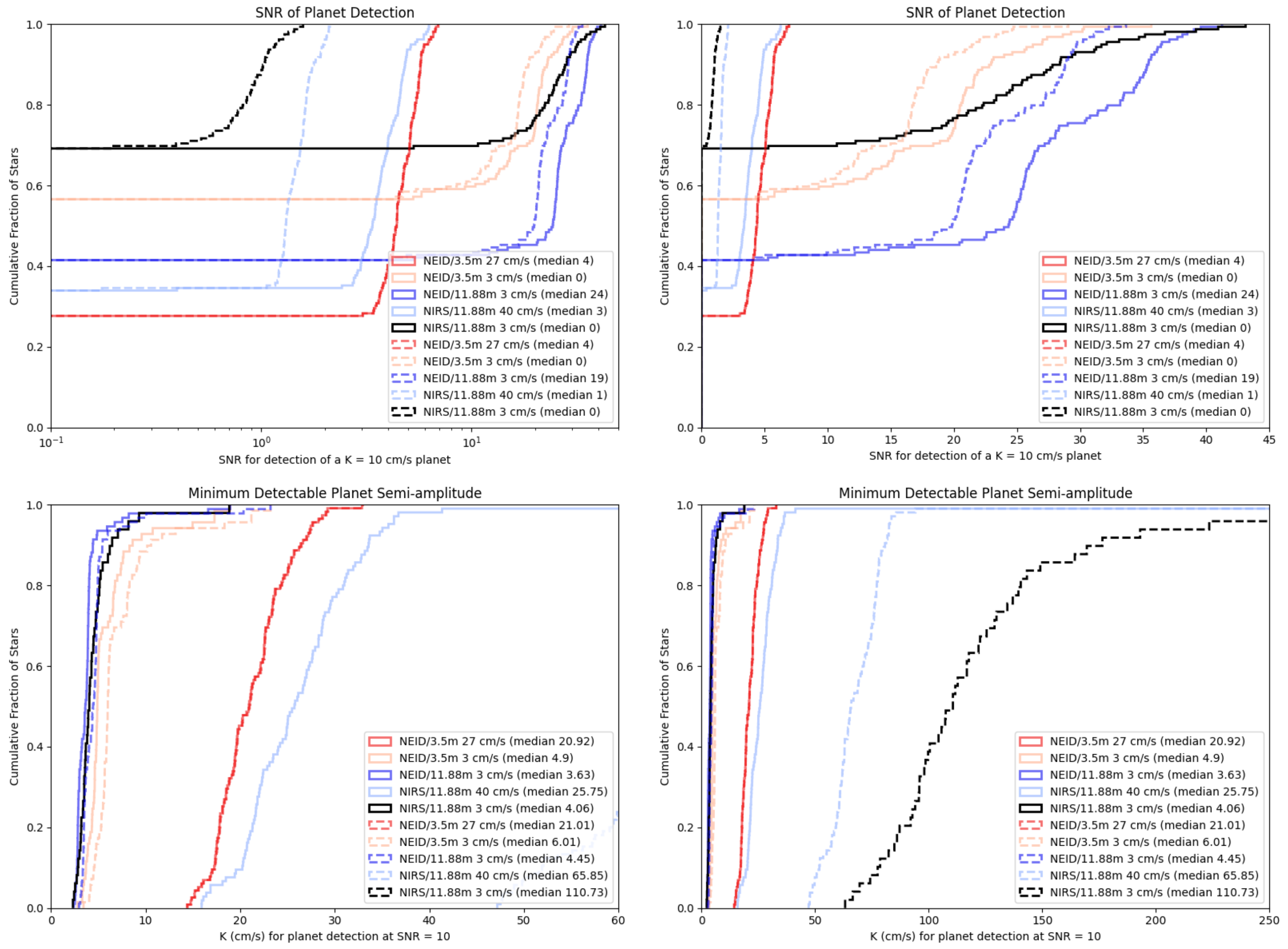

Figure: Detection sensitivity in terms of SNR for a planet with K = 10 cm/s, and smallest K for SNR = 10 under differing survey conditions. Solid lines are with no microtellurics (0 cm/s), dotted are with 3 cm/s (vis) and 115 cm/s (nir).

Conclusions and Future Work

At least some forms of stellar activity are "solveable" without meaningfully impacting survey perfomrance.

Target list shaping remains important, with hotter and more rapidly rotating stars being unsuitable for EPRV surveys, regardless of other factors (eg: stellar activity).

Atmospheric noise needs additional modeling in the IR, though is increasingly tractible in the visble.

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