

Joint Radial Velocity and Direct Imaging Planet Yield Calculations. II: Radial Velocity Scheduling and Cadence

2 PATRICK D. NEWMAN,¹ PETER PLAVCHAN,¹ JUSTIN CREPP,² SHANNON DULZ,² STEPHEN KANE,³
3 RHONDA MORGAN,⁴ CHRIS STARK,⁵ GIJS MULDER,⁶ SARA SEAGER,⁷ AND B. SCOTT GAUDI⁸

4 ¹*Department of Physics and Astronomy, George Mason University, 4400 University Drive, MSN 3F3, Fairfax, VA*
5 *22030*

6 ²*Department of Physics, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556, USA*

7 ³*Department of Earth and Planetary Sciences, University of California, Riverside, CA 92521, USA*

8 ⁴*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA*

9 ⁵*Space Telescope Science Institute*

10 ⁶*Universidad Adolfo Ibez, Santiago de Chile*

11 ⁷*MIT*

12 ⁸*Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH 43210*

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1. INTRODUCTION

1.1. *History*

While planet detection methods have greatly diversified since the first discoveries (Mayor & Queloz 1995), precision radial velocities remain a key component. The radial velocity method is still the second most common detection method and a key technique to confirm and parameterize exoplanets. It also probes a portion of the mass/radius - distance/period space that is inaccessible to other methods, and has a clear path forwards to achieving the precision needed to detect and characterize an earth-equivalent planet around a sun-equivalent star.

Simulating RV surveys to best determine direct imaging targets have a significant history, though have generally stopped at around the then available precision. eg: Howard & Fulton (2016) performed injection and recovery tests to determine yields and completeness, though were limited what sorts of information could be supplied (since only ice giant and gas giant planets could be firmly detected). Directly detecting terrestrial planets and providing mass estimates may soon be feasible, as opposed to just limiting the parameter space. Bottom et al. (2013) looked across multiple spectral types and wavelength ranges (including atmospheric windows), finding brighter, and therefore hotter, stars to generally be more suitable. Less generally, the CARMENES radial velocity survey has developed a highly detailed simulation system related to their spectrograph, telescope, and observation strategy. (Garcia-Piquer et al. 2017) This simulation is used in part used for night to night planning.

Surveys are increasingly automated, though how to maximize planet yield is only beginning to be studied. [Handley et al. \(2024b\)](#)

The latest generation of Doppler RV facilities such as: NEID ([Halverson et al. 2016](#)), EXPRES ([Jurgenson et al. 2016](#)), ESPRESSO ([Pepe et al. 2021a](#)), and MAROON-X ([Seifahrt et al. 2018](#)) are reaching into 30 cm/s and lower single measurement precisions. It is currently expected that future ones will get down to around 10 cm/s, though significant obstacles remain.

1.2. Motivation

There remains considerable debate on the value of η_{\oplus} ([Bergsten et al. 2022](#); [Bryson et al. 2021](#); [Kunimoto & Matthews 2020](#); [Bryson et al. 2020](#); [Dulz et al. 2020](#); [Pascucci et al. 2019](#); [Hsu et al. 2019](#); [Zink & Hansen 2019](#); [Garrett et al. 2018](#); [Kopparapu et al. 2018](#); [Mulders et al. 2018](#); [Burke et al. 2015](#); [Foreman-Mackey et al. 2014](#); [Petigura et al. 2013](#); [Dong & Zhu 2013](#); [Youdin 2011](#); [Bonfils et al. 2013](#); [Kopparapu 2013](#); [Dressing & Charbonneau 2015](#); [Bergsten et al. 2023](#); [Kaminski et al. 2025](#); [Bryson et al. 2025](#); [Fernandes et al. 2025](#); [Silburt et al. 2015](#)), which will be difficult to resolve without characterization of the atmospheres of some tens of terrestrial planets.

Coronagraphic mission performance in particular is strongly affected by η_{\oplus} . Even for higher values, being able to skip the detection phase and proceed directly to characterization with an optimized observing schedule would improve performance.

Uninformed RV surveys generally choose bright and/or nearby stars due to having more photons to work with. Coronagraphic surveys also do so due to planet brightness, limited inner working angles, and greater angular scale. While early ground-based transit surveys focused on brighter stars, more recent and space-based ones have much reduced restrictions. They have found populations of exoplanets that are largely not amenable to detailed follow-up (especially atmospheric characterization).

Also, both (unlike transit) are looser in geometry requirements. The geometry means that there are nearby planets that are suitable for direct imaging that can be found with RVs, but not transits. The HabEx Interim Report ([Gaudi et al. 2018](#)) and related results point to a use for finding earth analogs that can be later characterized.

Even for a more general exoplanet demographics mission, masses from a precursor survey greatly assist in constraining atmospheric models. Both mass and radius are required to constrain exoplanet compositions. ([Rogers & Seager 2010](#)) In particular, more planet mass/radius measurements with smaller error bars and well quantified selection effects are needed to constrain the structure of the transition in between rocky and non-rocky planets. ([Rogers 2015](#))

Planet masses are also important for accurate atmospheric retrievals. Spectroscopy of planetary atmospheres can only find the mass to high precision in limited circumstances, ([de Wit & Seager 2013](#)) and characterizing secondary atmospheres has considerable uncertainty [Changeat et al. \(2020\)](#). Differing compositions (especially for super earths), can produce similar spectra for a wide array of masses. ([Batalha et al. 2017](#)) Clouds and high metallicity can make accurate atmospheric retrieval difficult without accurate mass estimates. For JWST, these are $\pm 50\%$ for initial characterization, and $\pm 20\%$ for spectroscopic errors to be more important than mass ones. ([Batalha et al. 2019](#)) Even in cases where atmospheric retrivals can be done with low quality mass priors, good orbit priors remain useful. ([Salvador et al. 2024](#))

In this paper, we present a multi-part pipeline for: generating a realistic radial velocity survey cadence for a given observing site telescope and properties, instrument and characteristics, desired radial velocity precision, and target list of nearby stars and associated known stellar parameters.

However, this paper is focused on the resulting cadence from this level of simulation fidelity compared to more simplistic assumptions. We have developed this software to be re-usable and flexible for considerations of other current and future radial velocity surveys, and the software is available online¹. For each target star/instrument/telescope/precision combination we estimate exposures times, and resulting radial velocity precision from synthetic spectra after accounting for a typical airmass for observations. We focus on: overall exposure times to get to desired EPRV precision targets, typical numbers of observations per star as a result of the star’s position and exposure time, and figures of merit for planet detection. In Section 2, we present the inputs to our simulation, and various telescope and instruments considered, as well as the target lists considered. In Section 3, we present how we calculate the estimated radial velocity precision and requisite exposure times. In Section 4, we present how observations are scheduled in a simulated survey for a given a target prioritization scheme. In Section 5, we present the results of the cadence of observations for the different scenarios we consider. Additionally, we calculate a K/SNR figure of merit for these cadences. In Section 9, we discuss the interesting highlights of our resulting cadences, and in Section 10 we present our conclusions and plans for future work.

2. SIMULATION INPUTS

2.1. Target Catalogs

Testing our code has different requirements from pathfinder EPRV surveys, and the requirements and target lists of the surveys are evolving over time. While most of our simulations are with a single catalog, we construct multiple catalogs for some comparisons.

Our primary catalog uses Habitable Worlds Observatory’s ExEP list (as of 2023-07-26) was also considered. This list (Mamajek & Stapelfeldt 2023, 2024) explicitly selects FGK stars and has cutoffs for $v \cdot \sin i$ and R_{hk} . This catalog (hereafter called “HWO”) lacks explicit $v \cdot \sin i$ values, so we added them from the literature. (Glebocki & Gnacinski 2005; Martínez-Arnáiz et al. 2010; Ammler-von Eiff & Reiners 2012; Brewer et al. 2016; Luck 2017; Hojjatpanah et al. 2019)

Our initial star list comes from a modification of a version of the HabEx target list, which contains 72 Hipparcos stars. Given the source, this list has parameters somewhat different from a typical uninformed RV survey. It does not select for low stellar activity, but for distance (consisting entirely of stars within 5 parsecs). Constructing a catalog of the required stellar properties (T_{eff} , radius, distance, $v \cdot \sin(i)$, $\log(g)$) was done via existing tables in VizieR (see table 2). This by necessity makes it somewhat heterogeneous.

For the simulations, this target list was altered by: 1) Adding the companion star in a distant binary (not in Hipparcos); 2) dropping an eclipsing binary; cutting all stars below -30 declination (motivated by all sites currently being considered being in Arizona. Other target lists did not use this cut, though the effect on the simulations was limited due to nature of the dispatch scheduler.). This left 53 stars. Three sub-lists were also generated: the baseline “full” survey, a “deep” one containing 9 stars of particular interest to the HabEx team, and 47 stars that had no known planets at this time. Many of the stars with known planets have hot jupiters, which are likely to preclude the existence of habitable zone terrestrial planets.

¹ Available at https://github.com/pdn4kd/dispatch_scheduler

This target list (“HabEx”) was run alongside synthetic catalogs for checking out code’s exposure times, coverage, and precision results to ensure that they were realistic.

A second run of this “HabEx” target list was also done without the declination cut for more directly getting exoplanet yields across our instrument types, sensitivities, and exposure timescales.

As a check, the catalog from Newman et al. (2023) (hereafter called the “EPRV target list”) is also used within our revised exposure considerations. This provides an “apples-to-apples” comparison with our previous work, by keeping the targets the same while varying the instruments and exposure parameters.

2.2. Telescope and Instrument Parameters

The simulations here all use telescopes in Arizona (see table 4). These all being northern hemisphere site would normally motivate a declination cut. We do not do so for this survey as a test of what the practical lower limit is. Our site locations are the standard ones listed for each telescope. Our weather is taken from Kitt Peak data (specifically WIYN, see figure 1), while MINERVA proper uses records from a survey of Mount Hopkins (Swift et al. 2015).

We assume constant throughput in our spectrographs, though with values that reflect their actual averages (table 1). These throughputs are at or below the low end of commonly reported values to to compensate for those being peak values during nights with seeing. That is, they should reflect overall averages of the systems.

Table 1. Peak system throughputs for current EPRV spectrographs. These are higher than the averages used in the various architectures, as they largely do not account for performance variations from varying seeing and wavelength.

| Spectrograph | Throughput | Source |
|--------------|-------------|------------------------|
| ESPRESSO | 10% | Pepe et al. (2021b) |
| EXPRES | 9-15% | Blackman et al. (2020) |
| MAROON-X | 7-8%, 11.5% | Seifahrt et al. (2020) |
| NEID | 6% | Schwab et al. (2019) |

3. RADIAL VELOCITIES

The radial velocity precision code² is an implementation and expansion of existing work (Beatty & Gaudi 2015). The major changes are: including macroturbulence when data is available, and aggregating radial velocity uncertainties across the visible/red/IR ranges if the spectrograph being simulated crosses them. This is expanded somewhat in that the telescope and instrument are simulated to the point of continuum atmospheric absorption/scattering, basic signal to noise considerations on each pixel, and exposure and readout times.

² Available at <https://github.com/pdn4kd/reimagined-palm-tree>

3.1. *Stellar Properties*

For the purpose of simulating RVs, stars are defined by: T_{eff} , $\log(g)$, $v \cdot \sin(i)$, metallicity, stellar radius, and distance. Effective temperature directly defines the atmosphere model used, while the rest scale RV content ($\log(g)$, $v \cdot \sin(i)$, metallicity) or brightness (radius, distance).

While Beatty uses an estimate of macroturbulence based on effective temperature, some catalogs in the literature have measured this parameter ([Brewer et al. 2016](#)). Literature values are used where available.

Table 2. The HabEx stars and their properties used in these simulations.

| RA (J2000) | Dec (J2000) | HIP | Vmag | Distance (pc) | Rstar | T _{eff} | log(g) | Metallicity | Vsini | Mstar | V _{mac} |
|------------|-------------|--------|------|---------------|---------------------|-------------------|-------------------|--------------------|-------------------|--------------------|-------------------|
| 12.095738 | 5.280615 | 3765 | 5.74 | 7.4604597 | 0.74 ¹ | 4937 ¹ | 4.54 ¹ | -0.22 ¹ | 0.7 ¹ | 0.69 ¹ | 1.7 ¹ |
| 12.276214 | 57.815186 | 3821 | 3.46 | 5.952735 | 1.05 ¹ | 5919 ¹ | 4.37 ¹ | -0.21 ¹ | 0.5 ¹ | 0.94 ¹ | 4.2 ¹ |
| 25.624008 | 20.268505 | 7981 | 5.24 | 7.467702 | 0.81 ¹ | 5190 ¹ | 4.51 ¹ | -0.03 ¹ | 0.1 ¹ | 0.78 ¹ | 2.0 ¹ |
| 26.017012 | -15.93748 | 8102 | 3.49 | 3.647372 | 0.82 ¹ | 5333 ¹ | 4.6 ¹ | -0.44 ¹ | 0.1 ¹ | 0.99 ¹ | 2.2 ¹ |
| 26.936811 | 63.8525 | 8362 | 5.63 | 9.976058 | 0.84 ¹ | 5344 ¹ | 4.54 ¹ | 0.01 ¹ | 0.8 ¹ | 0.89 ¹ | 2.3 ¹ |
| 41.049942 | 49.228447 | 12777 | 4.1 | 11.232169 | 1.31 ¹ | 6196 ¹ | 4.19 ¹ | 0.05 ¹ | 8.0 ¹ | 0.96 ¹ | 6.2 ¹ |
| 47.26675 | 49.613277 | 14632 | 4.05 | 10.534078 | 1.4 ¹ | 5938 ¹ | 4.18 ¹ | 0.13 ¹ | 3.4 ¹ | 1.07 ¹ | 4.3 ¹ |
| 55.81209 | -9.763394 | 17378 | 3.52 | 9.043226 | 2.34 ¹ | 5037 ¹ | 3.75 ¹ | 0.15 ¹ | 0.1 ¹ | 1.11 ¹ | 3.4 ¹ |
| 63.818 | -7.6528707 | 19849 | 4.43 | 5.0443907 | 0.83 ¹ | 5092 ¹ | 4.51 ¹ | -0.2 ¹ | 0.5 ¹ | 0.8 ¹ | 1.9 ¹ |
| 72.460045 | 6.9612756 | 22449 | 3.19 | 8.025682 | 1.34 ¹ | 6398 ¹ | 4.27 ¹ | 0.05 ¹ | 16.4 ¹ | 1.21 ¹ | 8.5 ¹ |
| 79.78531 | 40.099052 | 24813 | 4.69 | 12.645422 | 1.28 ¹ | 5873 ¹ | 4.26 ¹ | 0.11 ¹ | 0.1 ¹ | 1.08 ¹ | 3.9 ¹ |
| 143.9146 | 35.810135 | 47080 | 5.4 | 11.17943 | 0.97 ¹ | 5499 ¹ | 4.44 ¹ | 0.27 ¹ | 2.8 ¹ | 0.95 ¹ | 2.6 ¹ |
| 175.26256 | 34.201637 | 56997 | 5.31 | 9.541075 | 0.86 ¹ | 5502 ¹ | 4.52 ¹ | -0.07 ¹ | 2.2 ¹ | 0.9 ¹ | 2.6 ¹ |
| 176.62947 | -40.500355 | 57443 | 4.89 | 9.239582 | 0.94 ¹ | 5672 ¹ | 4.51 ¹ | -0.27 ¹ | 0.1 ¹ | 1.04 ¹ | 3.1 ¹ |
| 188.43561 | 41.35748 | 61317 | 4.24 | 8.371003 | 1.06 ¹ | 5884 ¹ | 4.42 ¹ | -0.18 ¹ | 0.1 ¹ | 1.07 ¹ | 4.0 ¹ |
| 199.60132 | -18.311195 | 64924 | 4.74 | 8.525149 | 0.97 ¹ | 5562 ¹ | 4.44 ¹ | -0.03 ¹ | 0.8 ¹ | 0.93 ¹ | 2.8 ¹ |
| 223.34903 | 19.152798 | 72848 | 6.0 | 11.535356 | 0.84 ¹ | 5258 ¹ | 4.47 ¹ | 0.06 ¹ | 4.4 ¹ | 0.77 ¹ | 2.1 ¹ |
| 236.61089 | 7.353073 | 77257 | 4.42 | 11.753643 | 1.38 ¹ | 5901 ¹ | 4.22 ¹ | 0.04 ¹ | 2.0 ¹ | 1.15 ¹ | 4.1 ¹ |
| 272.4059 | 38.457775 | 88972 | 6.38 | 11.097548 | 0.8 ¹ | 4970 ¹ | 4.51 ¹ | -0.1 ¹ | 0.1 ¹ | 0.76 ¹ | 1.8 ¹ |
| 293.08997 | 69.66118 | 96100 | 4.67 | 5.76668 | 0.79 ¹ | 5242 ¹ | 4.56 ¹ | -0.21 ¹ | 0.5 ¹ | 0.81 ¹ | 2.1 ¹ |
| 298.8283 | 6.4067636 | 98036 | 3.71 | 13.70802 | 3.17 ¹ | 5081 ¹ | 3.55 ¹ | -0.11 ¹ | 0.1 ¹ | 1.3 ¹ | 3.5 ¹ |
| 303.82245 | -27.032976 | 99825 | 5.73 | 8.823789 | 0.82 ¹ | 5071 ¹ | 4.5 ¹ | 0.05 ¹ | 1.2 ¹ | 0.78 ¹ | 1.9 ¹ |
| 331.75278 | 25.345112 | 109176 | 3.77 | 11.756408 | 1.42 ¹ | 6565 ¹ | 4.25 ¹ | -0.05 ¹ | 0.1 ¹ | 1.31 ¹ | 11.2 ¹ |
| 5.0177503 | -64.874794 | 1599 | 4.23 | 8.592542 | 1.055 ² | 5948 ² | 4.46 ² | -0.18 ² | 3.0 ² | 1.176 ² | ... |
| 6.4378004 | -77.25424 | 2021 | 2.82 | 7.474959 | 1.802 ² | 5873 ² | 4.08 ² | -0.09 ² | 4.0 ² | 1.433 ² | ... |
| 9.840858 | 21.250473 | 3093 | 5.88 | 11.107409 | 0.879 ² | 5221 ² | 4.45 ² | 0.16 ² | 1.1 ² | 0.799 ² | ... |
| 24.199345 | 41.40546 | 7513 | 4.1 | 13.468014 | 1.573 ² | 6213 ² | 4.25 ² | 0.12 ² | 9.6 ² | 1.62 ² | ... |
| 39.02039 | 6.8868704 | 12114 | 5.79 | 7.208766 | 0.7348 ² | 4866 ² | 4.66 ² | 0.0 ² | 2.9 ² | 0.909 ² | ... |
| 43.13387 | -12.769714 | 13402 | 6.05 | 10.380981 | 0.7532 ² | 5236 ² | 4.59 ² | 0.11 ² | 4.9 ² | 0.811 ² | ... |
| 49.44235 | -62.57532 | 15330 | 5.53 | 12.119742 | 0.9062 ² | 5699 ² | 4.58 ² | -0.22 ² | 2.9 ² | 1.128 ² | ... |
| 49.553413 | -62.506363 | 15371 | 5.24 | 12.078753 | 0.9721 ² | 5845 ² | 4.54 ² | -0.23 ² | 2.6 ² | 1.192 ² | ... |
| 49.8404 | 3.370198 | 15457 | 4.84 | 9.159186 | 0.917 ² | 5742 ² | 4.49 ² | 0.1 ² | 5.2 ² | 0.948 ² | ... |
| 49.98188 | -43.069782 | 15510 | 4.26 | 6.059871 | 0.928 ² | 5401 ² | 4.62 ² | -0.23 ² | 1.5 ² | 1.3 ² | ... |
| 75.20417 | -5.7536755 | 23311 | 6.22 | 8.813679 | 0.7579 ² | 4827 ² | 4.69 ² | 0.3 ² | 1.7 ² | 1.031 ² | ... |
| 92.56031 | -74.753044 | 29271 | 5.08 | 10.148163 | 0.9729 ² | 5587 ² | 4.5 ² | 0.05 ² | 1.7 ² | 1.103 ² | ... |
| 103.07521 | -5.173713 | 32984 | 6.58 | 8.7001915 | 0.665 ² | 4758 ² | 4.92 ² | -0.01 ² | 1.8 ² | 1.34 ² | ... |
| 114.82549 | 5.224993 | 37279 | 0.4 | 3.4973595 | 1.919 ² | 6543 ² | 3.99 ² | 0.03 ² | 5.7 ² | 1.32 ² | ... |
| 157.65659 | 55.980537 | 51459 | 4.82 | 12.850167 | 1.12 ² | 6126 ² | 4.34 ² | -0.05 ² | 2.1 ² | 0.994 ² | ... |
| 177.67383 | 1.7647179 | 57757 | 3.59 | 10.900371 | 1.639 ² | 6161 ² | 4.22 ² | 0.16 ² | 4.0 ² | 1.61 ² | ... |
| 178.24487 | 37.718678 | 57939 | 6.42 | 9.156671 | 0.659 ² | 4950 ² | 4.65 ² | -1.16 ² | 0.5 ² | 0.716 ² | ... |
| 197.9683 | 27.878183 | 64394 | 4.23 | 9.154994 | 1.063 ² | 6075 ² | 4.57 ² | 0.04 ² | 4.4 ² | 1.54 ² | ... |
| 209.38358 | 61.492863 | 68184 | 6.49 | 10.104072 | 0.802 ² | 4757 ² | 4.58 ² | 0.1 ² | 1.3 ² | 0.89 ² | ... |
| 224.36667 | -21.415476 | 73184 | 5.72 | 5.905977 | 0.6754 ² | 4744 ² | 4.76 ² | 0.1 ² | 2.6 ² | 0.951 ² | ... |
| 239.11327 | 15.661617 | 78072 | 3.85 | 11.120996 | 1.447 ² | 6262 ² | 4.18 ² | -0.14 ² | 10.9 ² | 1.16 ² | ... |
| 249.08937 | -2.3245835 | 81300 | 5.77 | 9.778039 | 0.791 ² | 5277 ² | 4.57 ² | 0.05 ² | 2.2 ² | 0.853 ² | ... |

Table 2 continued on next page

Table 2 (*continued*)

| RA (J2000) | Dec (J2000) | HIP | Vmag | Distance (pc) | Rstar | T _{eff} | log(g) | Metallicity | Vsini | Mstar | V _{mac} |
|------------|-------------|--------|-------|---------------|----------------------|---------------------|-----------------------|---------------------|----------------------|-----------------------|------------------|
| 259.76596 | -46.636234 | 84720 | 5.47 | 8.786574 | 0.777 ² | 5256 ² | 4.61 ² | -0.27 ² | 0.3 ² | 0.901 ² | ... |
| 302.1817 | -66.18207 | 99240 | 3.55 | 6.1076164 | 1.178 ² | 5590 ² | 4.31 ² | 0.26 ² | 2.3 ² | 1.045 ² | ... |
| 302.79974 | -36.10121 | 99461 | 5.32 | 6.051803 | 0.7422 ² | 4922 ² | 4.58 ² | -0.33 ² | 2.7 ² | 0.766 ² | ... |
| 348.32074 | 57.168354 | 114622 | 5.57 | 6.525711 | 0.751 ² | 4835 ² | 4.56 ² | 0.09 ² | 1.8 ² | 0.749 ² | ... |
| 53.232685 | -9.458262 | 16537 | 3.72 | 3.218021 | 0.7188 ² | 5146 ² | 4.57 ² | 0.0 ² | 2.4 ² | 0.708 ² | ... |
| 86.11579 | -22.448381 | 27072 | 3.59 | 8.969415 | 1.2 ³ | 6241 ⁴ | 4.19 ⁴ | -0.16 ⁴ | 8.9 ⁵ | 1.4 ⁶ | ... |
| 208.67116 | 18.397717 | 67927 | 2.68 | 11.341726 | 2.19 ³ | 6201.8 ⁷ | 3.96 ⁷ | 0.13 ⁷ | 11.3 ⁵ | 1.15 ⁸ | ... |
| 247.11726 | -70.084404 | 80686 | 4.9 | 12.105072 | 0.99 ³ | 5963 ⁹ | 4.45 ⁹ | -0.16 ⁹ | 2.4 ⁵ | 1.2 ^{6 8} | ... |
| 4.59542 | 44.02278 | 1475 | 8.13 | 3.5679882 | 0.388 ¹⁰ | 3603 ¹⁰ | 4.83 ^{10 99} | -0.3 ¹⁰ | 0.6 ¹¹ | 0.398 ¹⁰ | ... |
| 4.60779 | 44.02734 | 1475B | 11.04 | 3.5679882 | 0.1923 ¹⁰ | 3218 ¹⁰ | 4.92 ¹² | -0.3 ¹⁰ | 0.1 ¹¹ | 0.159 ¹⁰ | ... |
| 34.26346 | 34.22423 | 10644 | 4.84 | 10.845987 | 0.98 ³ | 5597 ¹³ | 3.92 ¹³ | -0.41 ¹³ | 8.6 ⁵ | 1.125 ^{8 99} | ... |
| 76.37773 | -57.472702 | 23693 | 4.71 | 11.650938 | 1.3 ³ | 6069 ⁹ | 4.45 ⁹ | -0.25 ⁹ | 17.3 ⁵ | 1.2 ^{6 8} | ... |
| 77.91909 | -45.018414 | 24186 | 8.86 | 3.9175744 | 0.43 ³ | 3524 ⁹ | 4.87 ⁹ | -0.5 ⁹ | 5.4 ⁵ | 0.49 ¹⁴ | ... |
| 82.86415 | -3.677229 | 25878 | 7.97 | 5.6908717 | 0.5735 ¹⁵ | 3850 ¹⁵ | 4.7 ¹² | 0.0 ¹² | 2.73 ¹⁶ | 0.633 ¹⁰ | ... |
| 92.64423 | -21.864643 | 29295 | 8.15 | 5.7740054 | 0.695 ¹⁶ | 3522 ¹⁶ | 5.0 ¹⁷ | 0.06 ¹⁶ | 1.6 ⁵ | 0.49 ¹⁴ | ... |
| 152.84225 | 49.454235 | 49908 | 6.6 | 4.8728194 | 0.6398 ¹⁵ | 4176 ¹⁵ | 4.55 ¹² | -0.05 ¹² | 2.5 ⁵ | 0.707 ¹⁰ | ... |
| 165.83414 | 35.96988 | 54035 | 7.49 | 2.54842 | 0.3924 ¹⁵ | 3532 ¹⁵ | 4.82 ¹² | -0.4 ¹² | 1.6 ⁵ | 0.386 ¹⁰ | ... |
| 217.42896 | -62.679485 | 70890 | 11.01 | 1.2947832 | 0.141 ¹⁸ | 3054 ¹⁹ | 5.21 ⁹⁹ | 0.19 ²⁰ | 0.0864 ²¹ | 0.118 | ... |
| 259.05566 | -26.546146 | 84478 | 6.33 | 5.9680114 | 0.72 ³ | 4380 ¹² | 4.71 ¹² | -0.27 ¹² | 3.3 ⁵ | 0.67 ⁸ | ... |
| 297.69583 | 8.868322 | 97649 | 0.76 | 5.142975 | 1.5 ³ | 7550 ⁹ | 4.13 ⁹ | -0.24 ⁹ | 211.0 ⁵ | 1.74 ²² | ... |
| 316.72476 | 38.749416 | 104214 | 5.2 | 3.482743 | 0.728 ³ | 4242 ¹² | 4.7 ¹² | -0.38 ¹² | 2.0 ⁵ | 0.67 ⁸ | ... |
| 316.73026 | 38.742054 | 104217 | 6.05 | 3.5036085 | 0.601 ¹⁵ | 4025 ¹⁵ | 4.49 ¹³ | -0.41 ¹³ | 1.6 ⁵ | 0.641 ¹⁰ | ... |
| 319.31363 | -38.867363 | 105090 | 6.69 | 3.9467971 | 0.72 ³ | 3796 ²³ | 4.55 ²³ | -0.62 ²³ | 0.9 ⁵ | 0.58 | ... |
| 321.61087 | -65.366196 | 105858 | 4.21 | 9.21659 | 1.0 ³ | 6150 ²⁴ | 4.35 ²⁴ | -0.66 ²⁴ | 3.4 ⁵ | 0.932 | ... |
| 330.84024 | -56.785976 | 108870 | 4.69 | 3.6263416 | 0.84 ³ | 4500 ⁹ | 4.7 ⁹ | 0.04 ⁹ | 1.4 ⁵ | 0.67 ⁸ | ... |
| 344.10022 | -31.565567 | 113283 | 6.48 | 7.6370854 | 0.65 ²⁵ | 4555 ⁹ | 4.53 ⁹ | -0.01 ⁹ | 2.6 ⁵ | 0.77 | ... |
| 346.46683 | -35.85307 | 114046 | 7.35 | 3.2905562 | 0.468 ¹⁰ | 3688 ¹⁰ | 4.79 ^{10 99} | -0.06 ¹⁰ | 0.9 ⁵ | 0.495 ¹⁰ | ... |

Table 3. The HWO stars and their properties used in these simulations.

| RA (J2000) | Dec (J2000) | HIP | Vmag | Distance (pc) | Rstar | T _{eff} | log(g) | Metallicity | Vsini | Mstar |
|-------------|-------------|---------|-------|---------------|-------|------------------|--------|-------------|-------|-------|
| 129.7987692 | 65.0209064 | 42438 | 5.63 | 14.4388 | 0.946 | 5893 | 4.53 | -0.07 | 9.3 | 1.08 |
| 137.2127933 | 33.8822184 | 44897 | 5.962 | 18.9498 | 1.045 | 5992 | 4.5 | 0.04 | 4.4 | 1.08 |
| 147.1473806 | 46.0210074 | 48113 | 5.086 | 18.8226 | 1.604 | 5893 | 4.12 | 0.1 | 2.9 | 1.08 |
| 157.6565803 | 55.9805388 | 51459 A | 4.82 | 12.9452 | 1.111 | 6164 | 4.43 | -0.12 | 8.6 | 1.18 |
| 178.2448639 | 37.7186817 | 57939 | 6.427 | 9.1718 | 0.6 | 5057 | 4.64 | -1.33 | 2.9 | 0.85 |
| 188.01761 | -16.1960052 | 61174 | 4.297 | 18.2437 | 1.517 | 6871 | 4.242 | -0.06 | 66.8 | 1.44 |
| 188.4356011 | 41.3574781 | 61317 | 4.26 | 8.4727 | 1.034 | 5878 | 4.42 | -0.2 | 2.8 | 1.08 |
| 198.0132679 | -37.8030222 | 64408 | 4.847 | 20.4628 | 2.116 | 5688 | 3.92 | 0.16 | 2.7 | 0.99 |

Table 3 *continued on next page*

¹ Brewer et al. (2016), ² Valenti & Fischer (2005), ³ Pasinetti Fracassini et al. (2001), ⁴ Rich et al. (2017), ⁵ Glebocki & Gnacinski (2005), ⁶ Assumed, ⁷ Kunder et al. (2017), ⁸ ISBN 0199697140, ⁹ (Soubiran et al. 2016), ¹⁰ Mann et al. (2015), ¹¹ Newton et al. (2016), ¹² (Prugniel et al. 2011), ¹³ (Prugniel et al. 2007), ¹⁴ Kaltenegger & Traub (2009), ¹⁵ Newton et al. (2015), ¹⁶ Houdebine (2010), ¹⁷ Rajpurohit et al. (2013), ¹⁸ Demory et al. (2009), ¹⁹ Boyajian et al. (2012), ²⁰ Edvardsson et al. (1993), ²¹ Kiraga & Stepien (2007), ²² Adelman (2004), ²³ Koleva & Vazdekis (2012), ²⁴ Ramírez et al. (2013), ²⁵ Gáspár et al. (2016), ⁹⁹ Calculated

Table 3 (*continued*)

| RA (J2000) | Dec (J2000) | HIP | Vmag | Distance (pc) | Rstar | T _{eff} | log(g) | Metallicity | Vsini | Mstar |
|-------------|-------------|---------|-------|---------------|-------|------------------|--------|-------------|-------|-------|
| 218.6700724 | 29.7451271 | 71284 | 4.465 | 15.756 | 1.306 | 6745 | 4.26 | -0.41 | 8.1 | 1.39 |
| 230.4506246 | -48.3176305 | 75181 | 5.655 | 14.7391 | 1.046 | 5685 | 4.37 | -0.34 | 2.4 | 1.02 |
| 238.168921 | 42.4515175 | 77760 | 4.608 | 15.8975 | 1.742 | 5820 | 4.06 | -0.47 | 3.4 | 1.08 |
| 239.1132612 | 15.6616168 | 78072 | 3.843 | 11.2537 | 1.47 | 6285 | 4.14 | -0.18 | 9.9 | 1.25 |
| 246.0053797 | -39.1929805 | 80337 | 5.37 | 12.8923 | 0.968 | 5868 | 4.53 | 0.05 | 2.2 | 1.07 |
| 266.0362631 | -51.8340532 | 86796 | 5.124 | 15.6042 | 1.383 | 5761 | 4.25 | 0.29 | 3.8 | 1 |
| 271.5988313 | -36.0197863 | 88694 A | 5.949 | 17.1146 | 0.98 | 5892 | 4.38 | -0.05 | 7.3 | 1.08 |
| 272.4059009 | 38.4577772 | 88972 | 6.377 | 11.0959 | 0.794 | 5028 | 4.5 | -0.18 | 0.6 | 0.78 |
| 291.2424999 | 11.9444135 | 95447 | 5.169 | 14.922 | 1.393 | 5593 | 4.19 | 0.38 | 1.9 | 0.95 |
| 296.6066669 | 33.7275982 | 97295 A | 5.005 | 20.9857 | 1.503 | 6455 | 4.26 | 0.03 | 8.2 | 1.29 |
| 304.3805338 | 66.853689 | 100017 | 5.922 | 17.4813 | 0.999 | 5930 | 4.48 | -0.1 | 2.7 | 1.08 |
| 316.730266 | 38.742044 | 104217 | 6.043 | 3.4964 | 0.551 | 4107 | 4.47 | -0.21 | 1.8 | 0.63 |
| 330.8402234 | -56.7859786 | 108870 | 4.674 | 3.6384 | 0.728 | 4641 | 4.29 | -0.13 | 1.4 | 0.72 |
| 2.9334212 | -35.1331147 | 950 | 5.241 | 21.7191 | 1.375 | 6495 | 4.3 | -0.11 | 10 | 1.33 |
| 12.5316207 | -10.6443289 | 3909 | 5.176 | 15.923 | 1.153 | 6208 | 4.39 | -0.12 | 3.9 | 1.21 |
| 24.9492196 | -56.1933179 | 7751 A | 5.764 | 8.1894 | 0.775 | 5025 | 4.6 | -0.24 | 1.8 | 0.78 |
| 25.6240105 | 20.2685127 | 7981 | 5.241 | 7.6439 | 0.828 | 5204 | 4.49 | -0.04 | 0.1 | 0.85 |
| 34.7437699 | -25.9456872 | 10798 | 6.336 | 12.8347 | 0.762 | 5401 | 4.59 | -0.49 | 2.7 | 0.94 |
| 49.4423477 | -62.5753201 | 15330 | 5.513 | 12.0447 | 0.911 | 5710 | 4.5 | -0.23 | 2.7 | 1.01 |
| 49.9818788 | -43.069782 | 15510 | 4.258 | 6.0414 | 0.913 | 5432 | 4.46 | -0.39 | 0.9 | 0.97 |
| 56.7120305 | -23.2497228 | 17651 | 4.21 | 17.7847 | 1.678 | 6685 | 4.141 | 0.08 | 13.2 | 1.33 |
| 71.9012154 | -16.9344557 | 22263 | 5.489 | 13.24 | 0.962 | 5833 | 4.49 | 0 | 2.9 | 1.04 |
| 84.2911952 | -80.4691207 | 26394 | 5.666 | 18.2874 | 1.153 | 5982 | 4.39 | 0.09 | 2.7 | 1.08 |
| 86.1157942 | -22.4483855 | 27072 A | 3.596 | 8.905 | 1.28 | 6313 | 4.35 | -0.08 | 7.2 | 1.23 |
| 101.6847372 | 43.5774246 | 32480 | 5.252 | 16.6106 | 1.224 | 6066 | 4.38 | 0.11 | 3.6 | 1.14 |
| 103.0752106 | -5.1737127 | 32984 A | 6.562 | 8.7447 | 0.687 | 4767 | 4.54 | 0.02 | 2.7 | 0.79 |
| 105.9888134 | -43.608035 | 34065 | 5.56 | 17.0593 | 1.213 | 5790 | 4.33 | -0.22 | 3.6 | 1.04 |
| 108.9589132 | 47.2399634 | 35136 | 5.559 | 16.8518 | 1.157 | 5902 | 4.32 | -0.32 | 2.9 | 1.14 |
| 103.8277765 | 25.3756954 | 33277 | 5.763 | 17.4047 | 1.08 | 5924 | 4.44 | -0.12 | 2.9 | 1.08 |
| 219.9020583 | -60.8339927 | 71683 | 0.002 | 1.3319 | 1.231 | 5776 | 4.3 | 0.2 | 3.2 | 1.11 |
| 240.2610854 | 33.303511 | 78459 | 5.41 | 17.5108 | 1.328 | 5812 | 4.25 | -0.22 | 1.5 | 0.97 |
| 319.3136211 | -38.8673622 | 105090 | 6.69 | 3.9696 | 0.64 | 3874 | 4.78 | -0.01 | 0.9 | 0.59 |
| 12.0957332 | 5.2806137 | 3765 | 5.729 | 7.4352 | 0.728 | 5007 | 4.62 | -0.26 | 1.8 | 0.78 |
| 72.4600454 | 6.9612745 | 22449 | 3.184 | 8.0684 | 1.321 | 6443 | 4.3 | 0.03 | 15.3 | 1.25 |
| 327.0656298 | -47.3036161 | 107649 | 5.575 | 15.5589 | 1.039 | 5935 | 4.41 | -0.03 | 1.8 | 1.08 |
| 156.0987749 | -74.0316121 | 50954 | 3.99 | 16.2232 | 1.587 | 6905 | 4.228 | 0.05 | 40.7 | 1.43 |
| 199.6013083 | -18.3111938 | 64924 | 4.735 | 8.5344 | 0.982 | 5552 | 4.41 | -0.01 | 1.8 | 0.97 |
| 236.6108925 | 7.3530687 | 77257 | 4.422 | 11.9159 | 1.356 | 5898 | 4.18 | -0.01 | 3.3 | 1.09 |
| 303.8224641 | -27.0329754 | 99825 | 5.73 | 8.8116 | 0.818 | 5087 | 4.48 | 0.03 | 0.6 | 0.77 |
| 1.6532667 | 29.0215035 | 544 | 6.093 | 13.7662 | 0.889 | 5491 | 4.55 | 0.11 | 3.6 | 0.94 |
| 49.553412 | -62.5063624 | 15371 | 5.232 | 12.0394 | 0.983 | 5847 | 4.46 | -0.23 | 2.7 | 1.07 |
| 175.2625678 | 34.2016338 | 56997 | 5.308 | 9.5762 | 0.862 | 5491 | 4.54 | -0.05 | 2.3 | 0.94 |
| 259.0556767 | -26.5461491 | 84478 | 6.295 | 5.9537 | 0.66 | 4476 | 4.57 | -0.21 | 3.3 | 0.68 |
| 261.2504073 | 67.306708 | 85235 | 6.443 | 12.7919 | 0.761 | 5302 | 4.58 | -0.46 | 1.3 | 0.87 |
| 311.5238859 | -25.2708975 | 102485 | 4.137 | 14.6334 | 1.42 | 6638 | 4.238 | 0.04 | 42.2 | 1.33 |
| 332.5365841 | -32.5484084 | 109422 | 4.94 | 18.4579 | 1.405 | 6364 | 4.2 | 0.1 | 12.6 | 1.25 |
| 80.6397108 | 79.2311507 | 25110 | 5.08 | 20.7858 | 1.496 | 6354 | 4.2 | 0.12 | 11.7 | 1.21 |

Table 3 *continued on next page*

Table 3 (*continued*)

| RA (J2000) | Dec (J2000) | HIP | Vmag | Distance (pc) | Rstar | T _{eff} | log(g) | Metallicity | V _{sin i} | Mstar |
|-------------|-------------|---------|-------|---------------|-------|------------------|--------|-------------|--------------------|-------|
| 85.334732 | 53.481058 | 26779 | 6.2 | 12.2701 | 0.843 | 5226 | 4.52 | 0.1 | 3 | 0.88 |
| 133.5747796 | -5.4344595 | 43726 | 6.008 | 16.8465 | 0.983 | 5780 | 4.49 | 0.1 | 2.4 | 1.02 |
| 226.8252747 | 24.8691943 | 73996 | 4.94 | 19.536 | 1.451 | 6435 | 4.19 | -0.02 | 43 | 1.33 |
| 273.4743034 | 64.3972849 | 89348 | 4.99 | 23.1569 | 1.624 | 6473 | 4.09 | -0.29 | 9.7 | 1.33 |
| 349.1762648 | 53.2134748 | 114924 | 5.58 | 20.6102 | 1.286 | 6084 | 4.19 | 0.03 | 5.4 | 1.18 |
| 94.1109129 | 12.2721632 | 29800 | 5.04 | 19.5879 | 1.364 | 6480 | 4.307 | -0.03 | 17.1 | 1.33 |
| 145.5600675 | -23.9155672 | 47592 | 4.914 | 14.9515 | 1.233 | 6163 | 4.34 | -0.06 | 5.3 | 1.14 |
| 224.36667 | -21.4154798 | 73184 | 5.724 | 5.8864 | 0.732 | 4632 | 4.49 | 0.02 | 3.5 | 0.72 |
| 293.0899592 | 69.6611766 | 96100 | 4.672 | 5.7639 | 0.782 | 5298 | 4.52 | -0.21 | 1.8 | 0.87 |
| 75.2041639 | -5.7536734 | 23311 | 6.202 | 8.844 | 0.776 | 4810 | 4.46 | 0.31 | 1.4 | 0.75 |
| 81.106097 | 17.3835351 | 25278 | 5.009 | 14.5792 | 1.182 | 6131 | 4.29 | 0.01 | 14.4 | 1.18 |
| 49.8404013 | 3.3701986 | 15457 | 4.85 | 9.2762 | 0.946 | 5709 | 4.51 | 0.04 | 4.5 | 0.98 |
| 118.0652624 | -34.7054399 | 38423 A | 5.085 | 18.3274 | 1.246 | 6525 | 4.276 | -0.08 | 48.4 | 1.33 |
| 41.2758283 | -18.5726228 | 12843 | 4.465 | 14.2764 | 1.345 | 6330 | 4.36 | 0.07 | 27.3 | 1.21 |
| 321.6108541 | -65.3661981 | 105858 | 4.229 | 9.2584 | 1.086 | 6095 | 4.3 | -0.7 | 3.4 | 1.14 |
| 26.9368101 | 63.8525031 | 8362 | 5.626 | 10.0411 | 0.834 | 5358 | 4.48 | 0.03 | 0.9 | 0.9 |
| 272.6089738 | -62.00222 | 89042 | 5.469 | 17.7532 | 1.238 | 5951 | 4.29 | -0.07 | 4.2 | 1.08 |
| 5.0177443 | -64.8747937 | 1599 | 4.223 | 8.6071 | 1.063 | 5932 | 4.43 | -0.21 | 4.9 | 1.11 |
| 60.6531011 | -0.2689222 | 18859 | 5.361 | 18.707 | 1.206 | 6268 | 4.34 | 0.1 | 17.7 | 1.21 |
| 62.1525715 | 38.0397386 | 19335 | 5.522 | 21.1919 | 1.242 | 6381 | 4.61 | 0.19 | 16.2 | 1.18 |
| 25.6221438 | -53.740831 | 7978 | 5.52 | 17.3488 | 1.095 | 6155 | 4.44 | -0.04 | 5.4 | 1.14 |
| 354.9876724 | 5.626291 | 116771 | 4.132 | 13.7137 | 1.591 | 6200 | 4.15 | -0.14 | 6.3 | 1.21 |
| 265.8574731 | -21.6831941 | 86736 | 4.86 | 17.6523 | 1.335 | 6404 | 4.26 | -0.11 | 11.7 | 1.33 |
| 300.9058545 | 29.8968035 | 98767 | 5.745 | 16.0035 | 1.162 | 5563 | 4.32 | 0.22 | 0.8 | 0.96 |
| 348.320729 | 57.1683566 | 114622 | 5.54 | 6.5418 | 0.723 | 4874 | 4.56 | 0.06 | 1.8 | 0.75 |
| 13.2674852 | 61.123972 | 4151 | 4.8 | 18.8007 | 1.656 | 6105 | 4.11 | 0.05 | 8.6 | 1.18 |
| 349.2403645 | -62.0011978 | 114948 | 5.655 | 20.4426 | 1.16 | 6280 | 4.37 | -0.03 | 7.6 | 1.25 |
| 18.7963393 | -45.5316646 | 5862 | 4.966 | 15.2609 | 1.263 | 6110 | 4.34 | 0.16 | 4.7 | 1.14 |
| 302.1817036 | -66.1820674 | 99240 | 3.556 | 6.0993 | 1.198 | 5576 | 4.29 | 0.35 | 2 | 0.94 |
| 165.8341451 | 35.9698823 | 54035 | 7.421 | 2.5461 | 0.363 | 3601 | 4.87 | -0.42 | 1.6 | 0.44 |
| 209.3835765 | 61.4928612 | 68184 | 6.488 | 10.0672 | 0.759 | 4867 | 4.56 | 0.2 | | 0.75 |
| 26.0170131 | -15.9374799 | 8102 | 3.496 | 3.6522 | 0.826 | 5356 | 4.53 | -0.51 | 0.9 | 0.94 |
| 87.1455844 | -4.0946449 | 27435 | 5.973 | 15.2104 | 0.922 | 5731 | 4.47 | -0.22 | 2.7 | 1.02 |
| 249.0893737 | -2.324587 | 81300 | 5.764 | 9.8939 | 0.818 | 5262 | 4.52 | 0.03 | 1.6 | 0.87 |
| 125.0160865 | 27.217705 | 40843 | 5.13 | 18.2233 | 1.32 | 6269 | 4.3 | -0.28 | 4.3 | 1.25 |
| 316.7247483 | 38.7494173 | 104214 | 5.211 | 3.4966 | 0.637 | 4441 | 4.51 | -0.13 | 1.8 | 0.68 |
| 130.8251265 | -38.8823808 | 42808 | 6.556 | 11.1917 | 0.753 | 4992 | 4.6 | 0.01 | 2.7 | 0.76 |
| 301.3865229 | -67.3208961 | 98959 | 6.07 | 17.9323 | 1.033 | 5730 | 4.42 | -0.19 | 1.8 | 1.02 |
| 11.4399705 | -47.5519841 | 3583 A | 5.795 | 15.0487 | 0.924 | 5887 | 4.65 | -0.04 | 3.6 | 0.98 |
| 55.8120856 | -9.7633919 | 17378 | 3.537 | 9.0888 | 2.245 | 5045 | 3.78 | 0.09 | 1 | 0.87 |
| 176.6294689 | -40.5003572 | 57443 A | 4.893 | 9.3195 | 0.97 | 5618 | 4.44 | -0.31 | 2.7 | 1.02 |
| 164.8665531 | 40.4302557 | 53721 | 5.037 | 13.8875 | 1.21 | 5880 | 4.3 | 0.02 | 3.1 | 1.07 |
| 260.1648644 | 32.4677439 | 84862 | 5.385 | 14.5863 | 1.163 | 5704 | 4.33 | -0.39 | 1.6 | 0.94 |
| 346.4668158 | -35.8530709 | 114046 | 7.33 | 3.2871 | 0.47 | 3680 | 4.88 | -0.22 | 0.9 | 0.49 |
| 43.1338674 | -12.7697133 | 13402 | 6.038 | 10.3605 | 0.78 | 5199 | 4.55 | 0.07 | 6.2 | 0.82 |
| 93.7119848 | 19.1564479 | 29650 | 5.2 | 21.7763 | 1.335 | 6539 | 4.29 | 0.03 | 8.6 | 1.29 |
| 79.7853144 | 40.0990514 | 24813 | 4.705 | 12.5625 | 1.279 | 5854 | 4.24 | 0.06 | 1.3 | 1.08 |

Table 3 *continued on next page*

Table 3 (*continued*)

| RA (J2000) | Dec (J2000) | HIP | Vmag | Distance (pc) | Rstar | T _{eff} | log(g) | Metallicity | Vsini | Mstar |
|-------------|-------------|----------|-------|---------------|-------|------------------|--------|-------------|-------|-------|
| 191.2475207 | 39.2789162 | 62207 | 5.958 | 17.5565 | 1.004 | 5889 | 4.38 | -0.53 | 1.8 | 1.14 |
| 197.9683076 | 27.878184 | 64394 | 4.23 | 9.1975 | 1.079 | 5996 | 4.42 | 0.06 | 4.5 | 1.11 |
| 152.8422498 | 49.4542364 | 49908 | 6.55 | 4.8706 | 0.636 | 4097 | 4.64 | 0.21 | 2.7 | 0.63 |
| 6.4377932 | -77.2542461 | 2021 | 2.82 | 7.4588 | 1.844 | 5806 | 4 | -0.12 | 3.4 | 1.08 |
| 124.599779 | -12.6321714 | 40693 | 5.951 | 12.5794 | 0.883 | 5423 | 4.53 | -0.03 | 2.2 | 0.93 |
| 243.9052928 | -8.3694395 | 79672 | 5.496 | 14.1369 | 1.041 | 5785 | 4.43 | 0.03 | 2.7 | 1.02 |
| 177.6738271 | 1.7647226 | 57757 | 3.602 | 10.929 | 1.679 | 6123 | 4.13 | 0.13 | 3.6 | 1.14 |
| 326.1305414 | 14.7719398 | 107350 | 5.942 | 18.133 | 1.006 | 5939 | 4.45 | -0.06 | 9.9 | 1.08 |
| 128.2145653 | -31.5008514 | 41926 | 6.378 | 12.1643 | 0.765 | 5261 | 4.56 | -0.39 | 1.8 | 0.85 |
| 344.100219 | -31.565564 | 113283 | 6.446 | 7.6015 | 0.697 | 4601 | 4.68 | 0.04 | 2.6 | 0.72 |
| 40.6394444 | -50.8002931 | 12653 | 5.395 | 17.3572 | 1.158 | 6157 | 4.43 | 0.15 | 5.4 | 1.14 |
| 53.2326854 | -9.458261 | 16537 | 3.718 | 3.2198 | 0.746 | 5098 | 4.55 | -0.08 | 1.9 | 0.78 |
| 54.2182654 | 0.4016645 | 16852 | 4.291 | 13.9204 | 1.623 | 5996 | 4.1 | -0.08 | 3.7 | 1.14 |
| 265.0992732 | -49.4155831 | 86486 | 4.762 | 20.9624 | 1.621 | 6620 | 4.161 | -0.22 | 14 | 1.39 |
| 2.8160752 | -15.4679779 | 910 | 4.895 | 18.8861 | 1.505 | 6190 | 4.09 | -0.36 | 4.8 | 1.18 |
| 47.2667471 | 49.6132784 | 14632 | 4.05 | 10.5774 | 1.404 | 5952 | 4.22 | 0.09 | 3.6 | 1.08 |
| 137.5981111 | 67.1340172 | 45038 A | 4.809 | 20.5169 | 1.68 | 6325 | 4.07 | -0.02 | 5.8 | 1.21 |
| 157.8409203 | -53.7154836 | 51523 | 4.897 | 22.0616 | 1.845 | 6155 | 3.83 | -0.4 | 8.3 | 1.16 |
| 222.8474519 | 19.1004499 | 72659 A | 4.54 | 6.7536 | 0.823 | 5487 | 4.54 | -0.14 | 3.5 | 0.96 |
| 258.8374326 | -26.602826 | 84405 B | 5.11 | 5.9478 | 0.725 | 5144 | 4.59 | -0.22 | 4.4 | 0.85 |
| 259.7659898 | -46.6362334 | 84720 A | 5.472 | 8.7911 | 0.817 | 5235 | 4.56 | -0.35 | 1.8 | 0.9 |
| 260.2515605 | -21.1129364 | 84893 A | 4.389 | 17.5187 | 1.484 | 6756 | 4.254 | -0.25 | 18.9 | 1.44 |
| 314.1972153 | -26.2963779 | 103389 | 5.709 | 21.1021 | 1.182 | 6270 | 4.35 | -0.01 | 13.7 | 1.2 |
| 336.2348695 | -57.7974559 | 110649 A | 5.318 | 20.3398 | 1.717 | 5660 | 4.13 | -0.03 | 1.8 | 1.02 |
| 338.6734824 | -20.7082158 | 111449 A | 5.21 | 23.0205 | 1.419 | 6605 | 4.274 | 0.03 | 34.7 | 1.35 |
| 9.8408558 | 21.2504758 | 3093 A | 5.863 | 11.1081 | 0.898 | 5203 | 4.47 | 0.14 | 1.8 | 0.86 |
| 41.0499442 | 49.2284485 | 12777 A | 4.1 | 11.1501 | 1.273 | 6263 | 4.39 | 0.01 | 8.6 | 1.21 |
| 48.0188742 | -28.987622 | 14879 A | 3.8 | 13.999 | 1.79 | 6195 | 3.95 | -0.22 | 5.7 | 1.25 |
| 63.8179984 | -7.6528697 | 19849 A | 4.415 | 5.0098 | 0.809 | 5133 | 4.52 | -0.29 | 0.9 | 0.86 |
| 119.4454762 | -60.3030719 | 38908 A | 5.592 | 16.1718 | 1.052 | 5997 | 4.52 | -0.31 | 2.7 | 1.11 |
| 18.9420379 | -68.8759448 | 5896 A | 4.912 | 23.2606 | 1.588 | 6436 | 4.021 | 0.03 | 61.1 | 1.35 |
| 297.7568487 | 10.4157201 | 97675 A | 5.122 | 19.4881 | 1.491 | 6134 | 4.22 | 0.12 | 2.8 | 1.25 |
| 92.5603024 | -74.753044 | 29271 A | 5.076 | 10.2129 | 0.99 | 5594 | 4.46 | 0.1 | 2.3 | 0.96 |
| 236.8712542 | -37.9163119 | 77358 A | 6.012 | 15.2465 | 0.959 | 5602 | 4.47 | 0.1 | 1.8 | 0.96 |
| 271.3644289 | 2.498947 | 88601 B | 6.061 | 5.1225 | 0.674 | 4475 | 4.64 | 0.03 | 3.7 | 0.78 |
| 24.9481863 | -56.1964481 | 7751 B | 5.876 | 8.1965 | 0.703 | 5111 | 4.63 | -0.19 | 2.5 | 0.77 |
| 112.4831549 | 49.6724594 | 36439 | 5.35 | 20.4021 | 1.292 | 6349 | 4.29 | -0.28 | 9.7 | 1.16 |
| 157.7696164 | 82.5586517 | 51502 A | 5.25 | 22.7302 | 1.316 | 6758 | 4.389 | -0.16 | 94.2 | 1.39 |
| 182.1034022 | -24.7288751 | 59199 A | 4.025 | 14.9365 | 1.439 | 6990 | 4.192 | -0.13 | 23.8 | 1.5 |
| 271.363535 | 2.5001463 | 88601 A | 4.22 | 5.1133 | 0.865 | 5298 | 4.52 | 0.06 | 4.3 | 0.88 |
| 86.1105697 | -22.4218374 | 27072 B | 6.142 | 8.8916 | 0.719 | 4950 | 4.33 | -0.14 | 4.3 | 0.81 |
| 154.93403 | 19.4709128 | 50564 | 4.792 | 21.2199 | 1.669 | 6410 | 4.123 | 0.09 | 17.5 | 1.35 |
| 199.2127143 | 17.017178 | 64797 A | 6.55 | 10.9869 | 0.781 | 4843 | 4.47 | -0.18 | 3.3 | 0.76 |
| 216.2991543 | 51.8507436 | 70497 A | 4.052 | 14.5307 | 1.696 | 6280 | 4.23 | -0.03 | 28.6 | 1.33 |
| 12.2762275 | 57.8151773 | 3821 A | 3.444 | 5.0098 | 1.068 | 5907 | 4.41 | -0.28 | 3.4 | 1.14 |
| 101.5589581 | 79.5648107 | 32439 A | 5.44 | 18.2023 | 1.17 | 6204 | 4.43 | -0.1 | 4.5 | 1.18 |
| 222.8460153 | 19.1019133 | 72659 B | 6.979 | 6.7486 | 0.652 | 4288 | 4.636 | 0.144 | 4.6 | 0.67 |

Table 3 *continued on next page*

Table 3 (*continued*)

| RA (J2000) | Dec (J2000) | HIP | Vmag | Distance (pc) | Rstar | T _{eff} | log(g) | Metallicity | V _{sin i} | Mstar |
|-------------|-------------|----------|-------|---------------|-------|------------------|--------|-------------|--------------------|-------|
| 302.7997449 | -36.1012088 | 99461 A | 5.297 | 6.0122 | 0.715 | 4980 | 4.62 | -0.52 | 0 | 0.76 |
| 150.252737 | 31.9236703 | 49081 A | 5.378 | 14.9263 | 1.186 | 5743 | 4.3 | 0.2 | 1.8 | 1 |
| 236.0075774 | 2.5151668 | 77052 A | 5.869 | 14.7927 | 0.942 | 5682 | 4.47 | 0.05 | 4.1 | 0.94 |
| 52.3444893 | -62.9375289 | 16245 A | 4.703 | 21.7816 | 1.658 | 6662 | 4.31 | -0.17 | 13.1 | 1.32 |
| 76.8625232 | 18.6450499 | 23835 | 4.915 | 15.9172 | 1.594 | 5691 | 4.06 | -0.2 | 2.36 | 1.04 |
| 258.8365985 | -26.6016992 | 84405 A | 5.07 | 5.9523 | 0.724 | 5132 | 4.53 | -0.22 | 4.3 | 0.85 |
| 173.6228602 | -32.8313397 | 56452 A | 5.956 | 9.559 | 0.751 | 5196 | 4.6 | -0.4 | 0.9 | 0.88 |
| 219.8960963 | -60.8375276 | 71681 | 1.35 | 1.3319 | 0.859 | 5244 | 4.54 | 0.24 | 3.52 | 0.94 |
| 143.9145925 | 35.8101325 | 47080 A | 5.402 | 11.2348 | 0.969 | 5518 | 4.44 | 0.34 | 2.3 | 0.94 |
| 133.1492129 | 28.3308208 | 43587 A | 5.96 | 12.5868 | 0.948 | 5292 | 4.4 | 0.32 | 2.2 | 0.95 |
| 198.5631031 | -59.1032372 | 64583 A | 4.913 | 18.24 | 1.475 | 6238 | 4.23 | -0.31 | 13.8 | 1.25 |
| 24.1993398 | 41.4054587 | 7513 A | 4.1 | 13.4916 | 1.611 | 6154 | 4.17 | 0.08 | 9 | 1.18 |
| 76.377732 | -57.4727047 | 23693 | 4.701 | 11.6927 | 1.064 | 6158 | 4.43 | -0.18 | 12 | 1.14 |
| 214.753732 | -25.815425 | 69965 A | 5.872 | 17.9888 | 0.978 | 6120 | 4.41 | -0.68 | 3.6 | 1.11 |
| 341.6732494 | 12.1728858 | 112447 A | 4.2 | 16.1509 | 1.852 | 6193 | 4.07 | -0.27 | 7.7 | 1.25 |

Table 4. The primary 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.

| 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 |

3.2. Exposure Time/Precision

In principle, it is possible to figure out exposure times “on the fly”. This is not done due to: the expectation that it would take too long/be too computationally intensive, and that the current atmospheric model does not have a very large effect on precision at high airmass. So a single “good but imperfect” time is used, with assumptions about what that should be.

The aspects of instrumentation considered by Beatty are: wavelength coverage, and the resolution of the spectrograph. This is expanded somewhat in that the telescope and instrument are simulated to the point of basic signal to noise considerations on each pixel, and exposure and readout times.

The readout noise formula is:

$$\frac{\text{photons} \cdot \text{gain}}{\text{pixels} \cdot \sqrt{\text{photons} \cdot \text{gain} / \text{pixels} + (\text{gain} \cdot \text{dnoise} \cdot 2.2 \cdot 2 \cdot \text{exposures})^2 + (\text{gain} \cdot \text{darkcurrent} \cdot \text{exptime})^2}} \quad (1)$$

A generic/other noise term is also included, which describes all unmodeled noise and is treated as an undefined part of an instrument’s noise budget. The generic/other noise is added in quadrature with the (readout) noise to give an overall noise level, which is assumed to be the standard deviation of a Gaussian. A random “measurement” is generated from this overall noise level, and then used for fitting once actual signals have been added in.

3.3. Exposure Time Estimation

Exposure time calculation is done via scaling assumptions in the high SNR regime. An initial “guess” is performed by finding the RV precision and SNR at the site when the detector is saturated at whatever wavelength the star is brightest at. To make the guess closer to reality, the signal is attenuated through the airmass at 10° off of zenith, and readout noise is doubled. These seemingly ad-hoc considerations are to consider that the actual exposure is likely to be a co-add of several shorter ones and at more than one airmass. The actual exposure time is then rescaled by a factor of $\left(\frac{\text{guessRV}}{\text{targetRV}}\right)^2$. If there is a signal to noise requirement, SNR is rescaled in the same way, and the longer time of it or radial velocity is used.

Times under a minimum are increased to that minimum so as to average out over p-mode oscillations. This is to minimize the effect of this noise source and convert it from correlated to uncorrelated.

In previous work (Newman et al. 2023), we used a fixed 5-minute (and then for comparison a fixed 10-minute) minimum. A more detailed look is appropriate here, as is calculating the actual p-mode timescales using our in-hand stellar properties.

As these times vary per-star, we look at the effects of instituting two fixed (5 minute and 10 minute), and two variable minimum times per star. The first of the variable versions scales with a star’s dynamical timescale $\tau \sim \sqrt{R^3/M}$, where we define the sun as having a time of 300 seconds:

$$T_{min} = 300 \sqrt{\frac{(R/R_{\odot})^3}{M/M_{\odot}}} \quad (2)$$

This is in contrast with Chaplin et al. (2019) and Luhn et al. (2023), which use surface gravity and effective temperature to find the pulsation frequency:

$$\nu = 3100 \mu Hz \left(\frac{g}{g_{\odot}} \right)^1 \left(\frac{T_{eff}}{T_{eff,\odot}} \right)^{-0.5} \quad (3)$$

Here, g is the actual surface gravity, and not $\log(g)$.

Our minimum period is then ν^{-1} . For the Sun this is 322 s, which is within 10% of the previous scaling. As shown in sections 7,6,8, outside of the short exposure limit, we don’t find particularly large differences in results for any p-mode compensation algorithm.

These just generate the “open shutter” time, so the number of exposures to avoid saturating the detector is counted, and the readout times added in to give a total exposure time. We do not impose any upper limit on exposure times, so depending on the input parameters, impractically large ones can be generated. That these stars rarely or never be observed is discussed in section 9, and points to how EPRV target selection must be done with care even in the absence of stellar activity.

3.4. Atmospheric Effects

Our atmospheric absorption/scattering model uses Rayleigh scattering plus a small baseline.

$$\tau = 0.09 + \left(\frac{3080 \text{\AA}}{\lambda} \right)^4 \quad (4)$$

This relation was found by fitting measurements from CFHT at Mauna Kea⁴, and Texas A&M University (Schmude 1994). Sky brightness and line absorption are not considered.

The above gives an optical depth at a specific wavelength and 1 airmass. actual absorption considers altitude and zenith angle using simple isothermal (default scale height 8400 m), and slab ($1/\cos(\theta)$) models, respectively.

This is sufficient for ultraviolet, visible, and the nearest infrared wavelengths, but breaks down once water absorption starts to matter (approximately 890 nm). Expanding into this range would be preferable, but would require line-by-line analysis instead of the current continuum model. This is a consideration for future work, but would significantly increase complexity.

Beyond reducing the strength of RV information, line-based absorption also introduces uncertainties which are not modeled here. Scattered/absorbed light is assumed to simply be lost, and any errors in

⁴ <https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/extinction>

lines from microtellurics are assumed to be perfectly modeled. We partially account for microtelluric errors with nominal noise values in section 6.4.

Clouds/hazes are not considered (beyond the wavelength-independent portion of the absorption acting as particulates), nor does the model include weather or season variations in sky quality. A night is assumed to be perfectly clear, or unusable/no observations are possible.

3.5. Stellar Activity

We do not directly model any form of stellar activity (eg: oscillations, granulation, spots/plages). Indirectly, we both choose a target list to contain relatively inactive stars (eg: low R_{HK} values), and our exposure times compensate for p-mode oscillations (see 3.3). We expect that observation campaigns with high cadence and a large number of observations can better model activity to reduce “jitter”, but this lack of direct modeling can lead to our expected sensitivities and SNRs being optimistic by a factor of several.

In contrast, Luhn et al. (2023) which models stellar variability with 4 terms: 1 for activity, 1 for oscillation, and 2 for granulation. The active regions use a solar-specific model, while oscillations and granulations consider spectral type. Our p-mode calculations herein substantially addresses the oscillation portion of the noise, as we look at: Luhn’s timescales, an alternate timescale that also scales with spectral type, and 2 fixed ones. Additional strategies are needed for the other forms of stellar variability. Both more realistic active regions, and observing strategies to mitigate active regions and granulation are deferred for future work.

4. DISPATCH SCHEDULER (SURVEY SIMULATIONS)

The dispatch scheduler simulates an observational campaign to generate observation time series for later use. Our version⁵ is derived from the MINERVA scheduler (Swift et al. 2015; Nava et al. 2015). The scheduler takes a list of targets with name, RA, Dec, and observation times as inputs, and generates a time series of observations for each target (as well as the Sun and each target’s rise and set times). It also generates a nightly summary file containing: start and end of the night, weather, number of times each star was observed, amount of time spent on each star, and if the star was observable at all given our constraints. Constraints define the ordering and prioritization of targets to observe. These observation constraints can be divided into: natural, observatory, and prioritization weights.

For natural constraints, we consider: latitude, longitude, local weather (fraction of clear nights), target acquisition, elevation, and local horizon. Calculated sun-rise/set times are used, and a minimum distance from the Moon is specified (ephemeris via Astropy). For the observatory constraints, we consider local horizon, acquisition/repointing time, and observation/readout time.

As per the name, we use a dispatch scheduler prioritization scheme. The scheduler determines target choices “on the fly”, and we consider several different prioritization weighting options that we discuss in Section 4.1.

A typical night works as follows:

- Advance time to “full dark” (configurable, by default astronomical twilight, where the sun is 12 degrees below the horizon)
- Check to see if the night is clear, or lost due to weather
- If the night is cloudy, advance time to dawn
- If the night is clear, prep target list (determining which stars are observable due to sufficient separation from the moon, and being above the horizon)
- Begin observation loop

Observation loop:

- Generate weightings for the target stars
- Pick highest weighted target
- If the target has a positive weight, observe it for the duration specified
- Wait five minutes (this is done whether or not a target is observed.)
- Repeat until dawn

Observations are recorded as they are taken. If no target has a positive weight, this means that no observations are taken with the telescope, and we record the telescope downtime separately. At dawn, we record the Sun and target rise and set times, a nightly summary of target observations observability and weather, and move to the next night. Dawn can be specified to mean that the sun

⁵ Available at https://github.com/pdn4kd/dispatch_scheduler

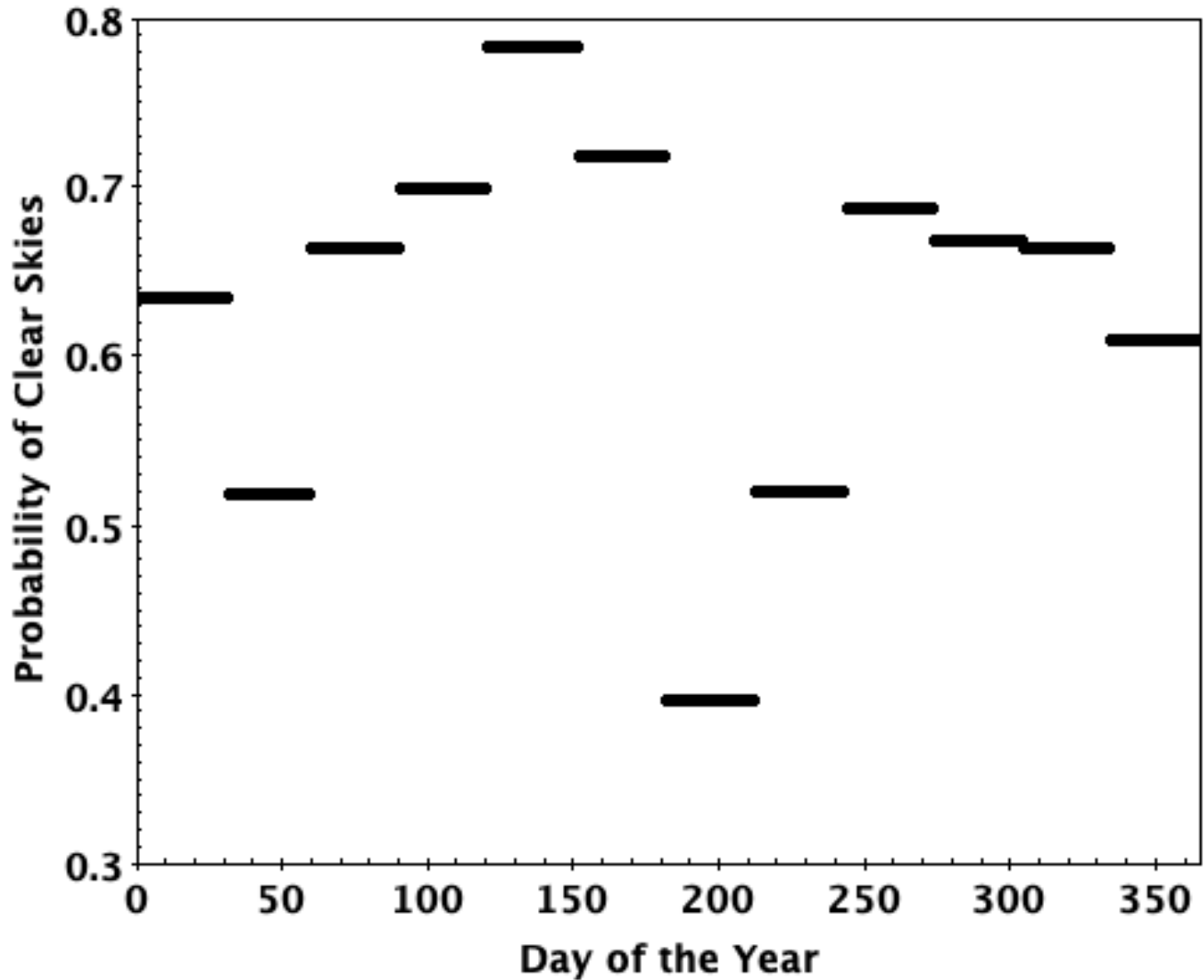


Figure 1. Monthly WIYN observing and weather statistics from 1999 to 2006. Adapted from http://www-kpno.kpno.noao.edu/Images/wiynWeather_stats.jpeg

is still below the horizon, depending on what settings are specified. Days/nights will alternate until the observation campaign is completed.

Finally, we assume that 100% of telescope time is available for a RV survey. Treating the weather as worse/lower probability of a clear night can effectively simulate random queuing without affecting the weighting system. Implementing bright/dark time scheduling would be a subject for future work, as the exact definition varies between observatories.

4.1. Target Weighting

As we do not plan our observations in advance, we need to figure out which star to observe multiple times per night. Our weighting constraints were chosen to maximize the total number of observations while minimizing the variance between stars. More observations are of obvious value, but we also expect that higher planet yields will be best served by relatively even survey depth. To achieve

these, we focused on weighting schemes using hour angle/meridian distance, as well as time since last observation.

Hour angle weighting is an attempt to maximize observation quality without penalizing stars at unfavorable declinations. It varies linearly from 1 at the meridian to 0 at the horizon. The time since last observation weighting is the number of days since last observation after the minimum separation between observations has passed. Before this it is set to 0. Regardless of other considerations, “unobservable” stars are assigned a weight of -999. Observable is defined as: above the nominal horizon for the duration of the observation, sufficiently far from the moon (10 degrees by default), and that the observation will finish before sunrise.

After iterating through different versions of these weightings (see section 9.4), we settled on using hour angle multiplied with time since last observation, with a minimum time of 2 hours. These combined weighting will in practice prioritize stars that have not been observed in a given night that are anywhere within a telescope’s pointing limits over ones that have at the zenith.

5. RESULTS (OVERVIEW)

In this section, we discuss the overall outline of the results, and what we look at in terms of outcomes. First we introduce figure of merit we use for detection efficiency (section 5.1), which along with exposure times and numbers of observations, we will use for all subsequent simulations that are not directly testing the survey simulation code. We then show a few example outputs before proceeding with the results of different target lists and simulation parameters:

We show example timeseries results in in Figure 2, before going into general target list results.

We primarily focus on the HWO target list. All results are for a surface gravity/effective temperature p-mode timescale and hour angle with 2 hour minimum observation separation target weighting. For this we show: exposure times, observations, and how those correlate; exposure times as a function of selected stellar parameters; observations as a function of selected stellar parameters. We show our detection heuristic/figure of merit in some plots, as well as how those detections are degraded by uncorrected telluric effects.

Detailed reasons for why we choose a specific p-mode compensation method and target weighting are described in 9.4.

The EPRV and HabEx target lists are then covered briefly, with more of their differences and how target list selection changes results in 9.6.

5.1. Figure of merit: planet semi-amplitude sensitivity and detection SNR

Herein, we use a figure of merit for detecting a plausible planet with some simplifying assumptions: For an uninformed survey where the period observed is much longer than than the planet, the planet's orbit is circular and edge-on, and the distribution of observations is random/planet phase is unknown (Gaudi & Winn 2007):

$$SNR = \frac{K}{\sigma} \sqrt{\frac{N_{\text{obs}}}{2}} \quad (5)$$

$$K = SNR \cdot \sigma \sqrt{\frac{2}{N_{\text{obs}}}} \quad (6)$$

The noise term, σ , can be broken down into multiple noise sources added in quadrature (photon, instrument, tellurics, etc). eg:

$$SNR = \frac{K}{\sqrt{2}} \sqrt{\frac{N_{\text{obs}}}{\sigma_{\text{instrument}}^2 + \sigma_{\text{photon}}^2 + \sigma_{\text{atmosphere}}^2}} \quad (7)$$

$$K = SNR \cdot \sqrt{(\sigma_{\text{instrument}}^2 + \sigma_{\text{photon}}^2 + \sigma_{\text{atmosphere}}^2) \frac{2}{N_{\text{obs}}}} \quad (8)$$

For analysis in this paper, we use equations 7 and 8, with the atmospheric noise term being zero in all sections except for the telluric noise ones.

5.2. Example Timeseries

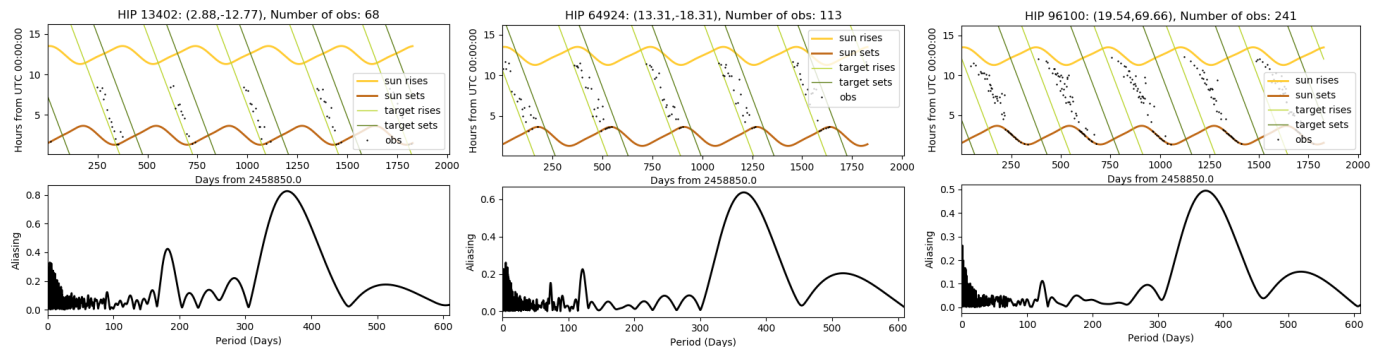


Figure 2. Example survey results from a 5 years/100% time with Super NEID (3 cm/s) on the WIYN. The top graph shows target rise and set times, sunrise and sunset times, and target observations over the course of the survey. The bottom graph shows potential aliasing/false planet signals from the distribution of observations over various orbital periods. Patterns in observations as a result of long exposure times and changing weighting are visible, as well sensitivity limitations for some planets.

6. RESULTS (HWO TARGET LIST)

6.1. Exposure Times and Observations

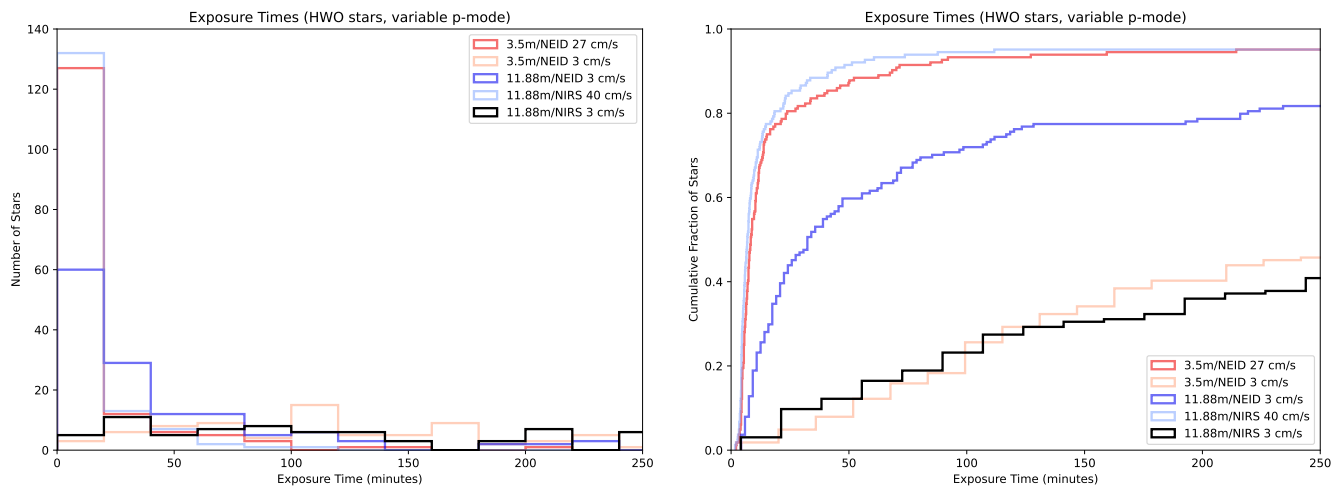


Figure 3. Exposure times as histograms (left) and cumulative distribution functions (right) for every star in our telescope/instrument combinations. There is a tail of stars with very long exposure times (and which are therefore difficult to observe at high precision). The PDF appears the same for all 3 sets of stars due to the current bin size of 20 minutes, as whatever chosen p-mode correction has little effect beyond that. Due to finer bin sizes, the CDFs do show that the exact distribution of exposure times is shuffled around somewhat, though the effect is again small (and largely confined to telescope/instrument/precision combinations that skew to shorter exposure times).

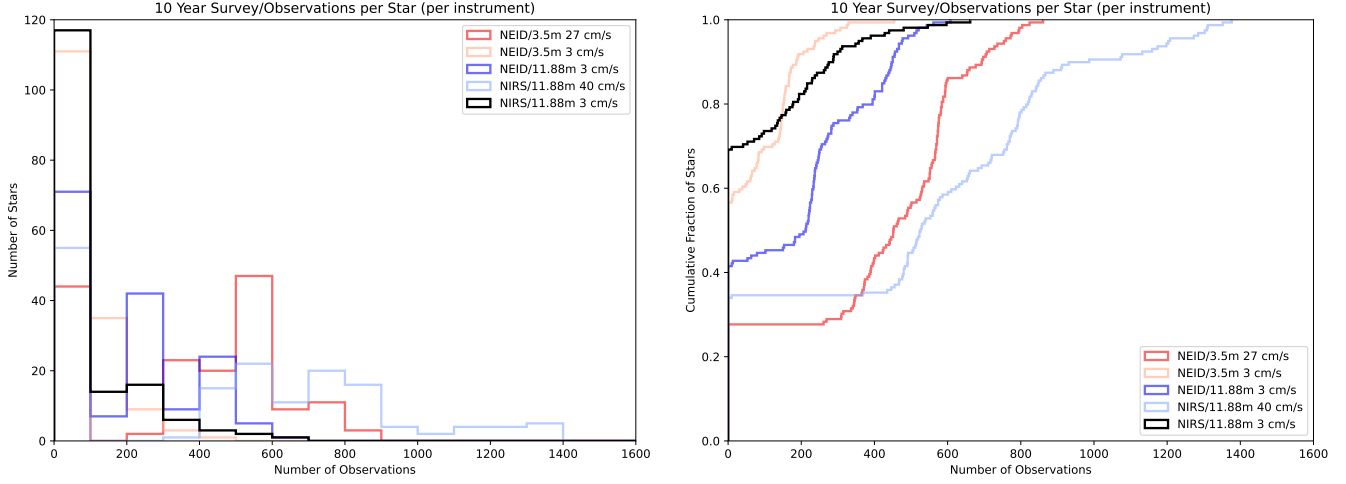


Figure 4. Histograms of total number of observations for the different telescope/instrument combinations as both PDFs (left) and CDFs (right). Differences between different architectures are quite obvious, though the ones between different p-mode compensation methods are subtle (and not apparent for the architectures with longer exposure times and fewer observations).

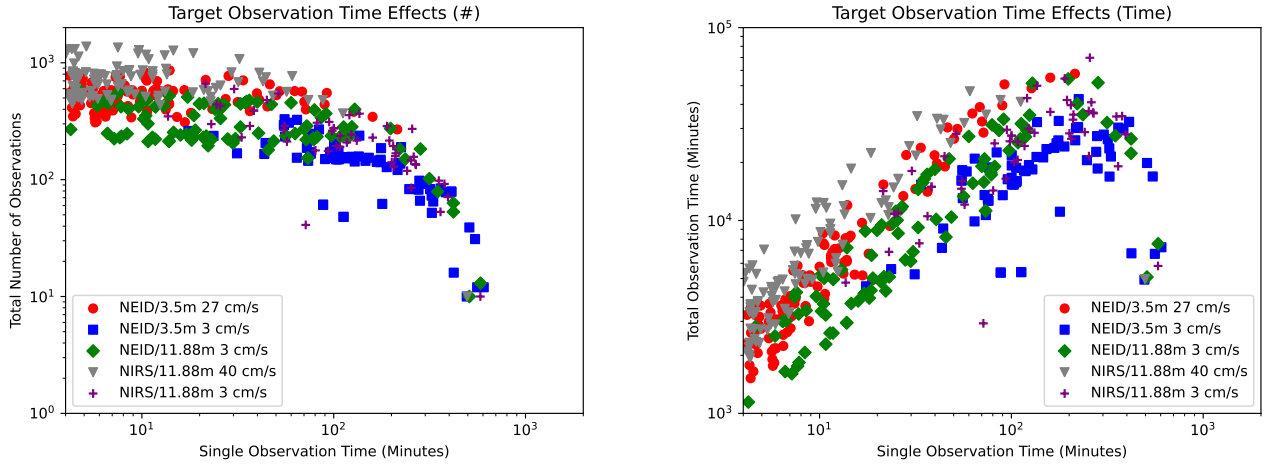


Figure 5. Total number of observations (left) and total time spent observing (right) for each star and telescope/instrument combination as a function of exposure time.

6.2. Exposure Times and Stellar Parameters

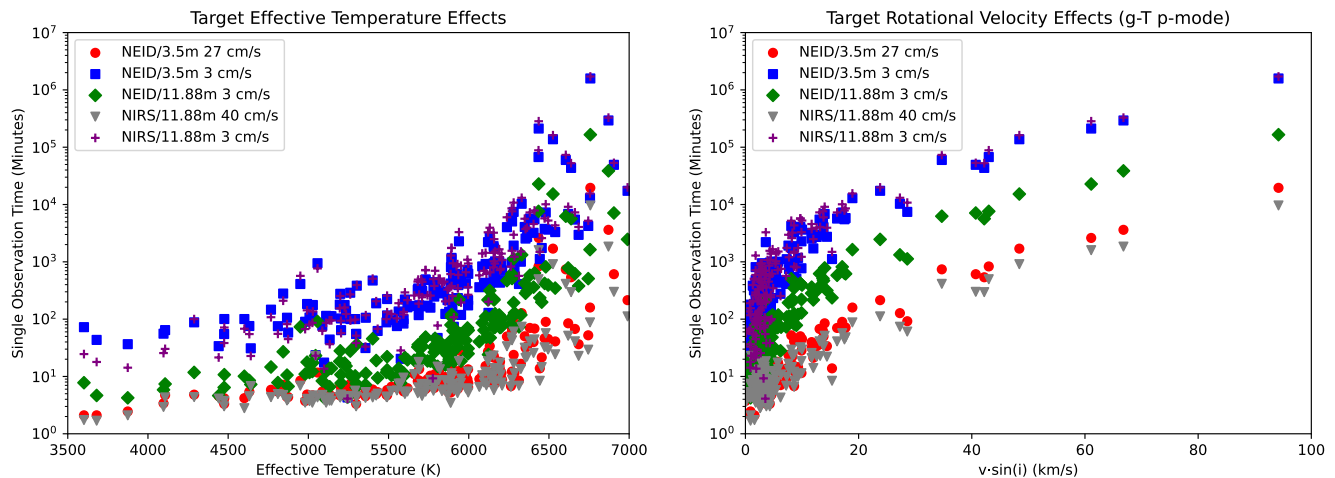


Figure 6. Exposure times as a function of effective temperature (left), and rotational velocity (right), for the gravity/effective temperature P-mode compensation. While we see clear trends of hotter/faster rotating stars being harder to observe, the choice of telescope/instrument/precision usually has a larger effect.

6.3. Right Ascension and Declination

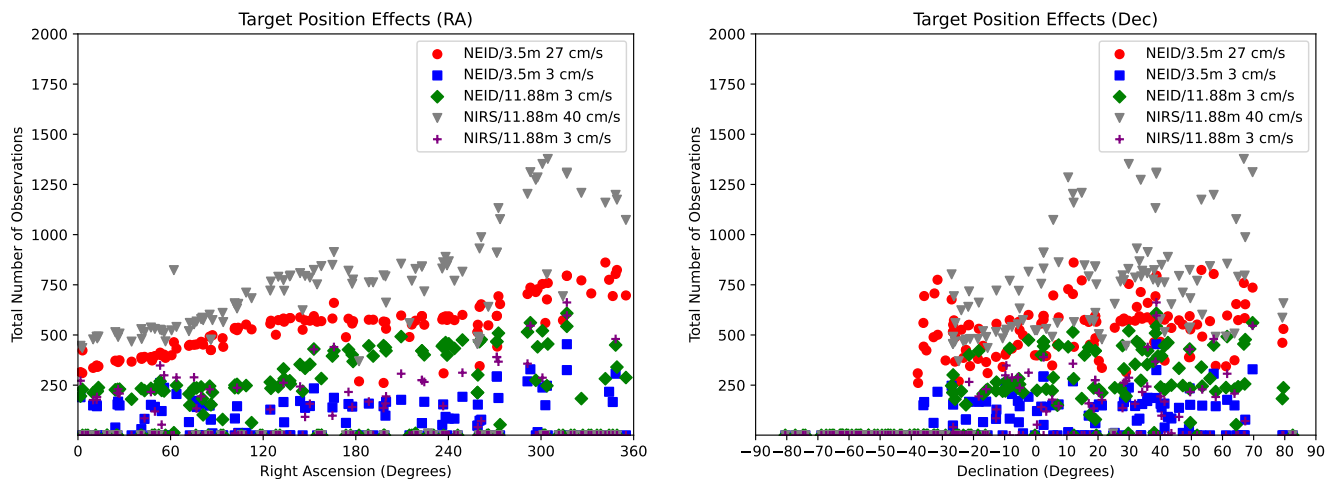


Figure 7. Total number of observations per star as a function of Right Ascension (left) and Declination (right). There is a clear trend in right ascension, we believe from a combination of night length and weather (though it is suppressed for longer exposure time telescope/instrument/precision combinations). That the larger peak corresponds with stars that have the longest time above the horizon in late summer (around 300-330 degrees) and not winter/early spring (when the weather is better and nights longer) is surprising. Declination does not show a clear trend, with number of observations per star being relatively flat north of about -40 degrees. Below that, stars are never observed.

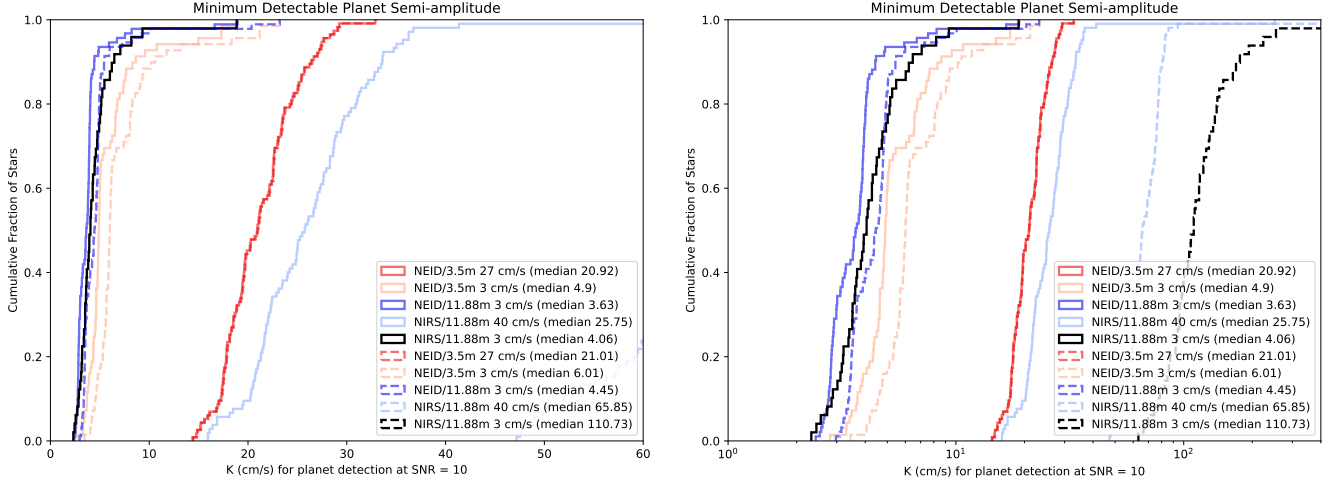


Figure 8. CDFs of minimum detectable reflex velocity (K , in cm/s) of a planet at $\text{SNR} = 10$ over our telescope/instrument combinations at multiple scales. The results with no microtellingurics are shown as solid lines, while the telluric noise are the dotted lines.

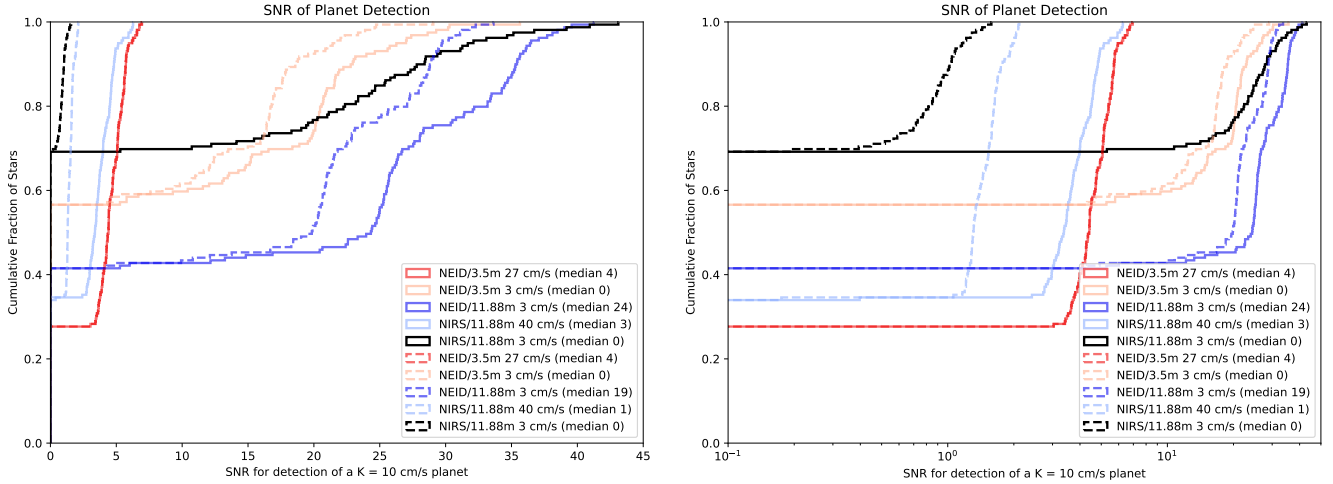


Figure 9. CDFs of minimum detectable reflex velocity (K , in cm/s) of a planet at $\text{SNR} = 10$ over our telescope/instrument combinations at multiple scales. The results with no microtellingurics are shown as solid lines, while the telluric noise are the dotted lines.

6.4. Telluric Corrections

Despite our earlier atmospheric assumptions, earth's atmosphere has many shallow lines that are difficult to correct for, especially in the infrared. To simulate this, we consider an additional noise term added in quadrature with the instrument and photon noise ones. We choose values of 3 cm/s for the visible spectrograph and 115 cm/s for the NIR spectrograph, which are in line with existing EPRV systems. (Wang et al. 2022)

As our assumed noise is smaller than the instrument and photon noise sources in all but the most optimistic visible surveys, microtellingurics have little effect. In contrast, this noise source dominates over all others in the NIR (being far larger than the instrument or photon components, even in the

most pessimistic cases), and must be better accounted for if this wavelength range is to be useful in the EPRV era.

7. RESULTS (HABEX TARGET LIST)

While a full set of simulations were done, for brevity we only post the most relevant ones, using the g-T p-mode compensation. We do not go over the results in particular detail, though some of the differences are discussed in section 9.

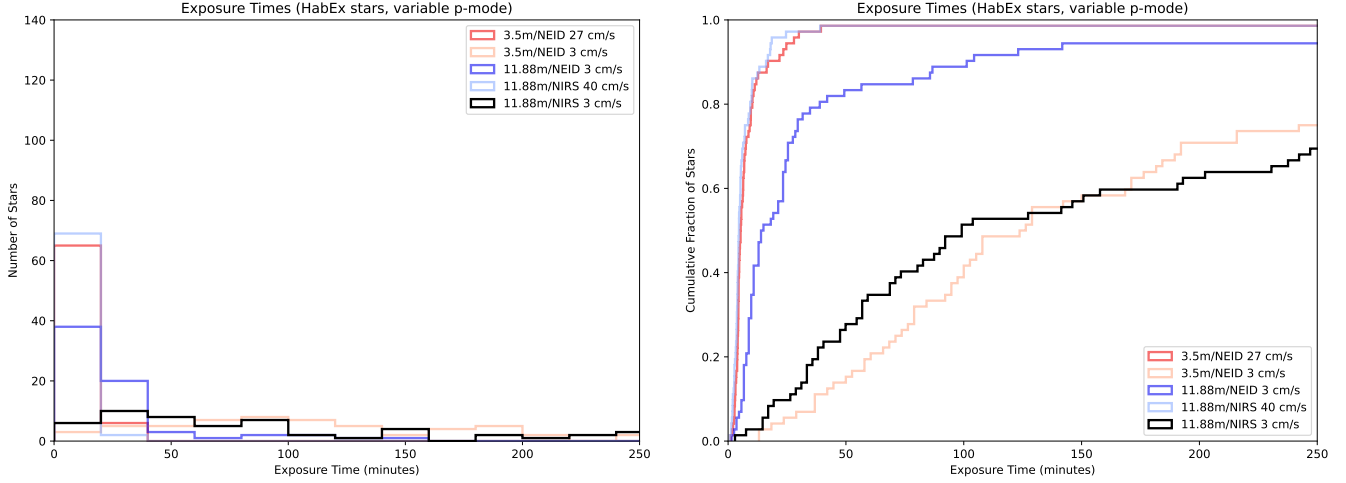


Figure 10. Exposure times as histograms (left) and cumulative distribution functions (right) for every star in our telescope/instrument combinations. There is a tail of stars with very long exposure times (and which are therefore difficult to observe at high precision). The PDF appears the same for all 3 sets of stars due to the current bin size of 20 minutes, as whatever chosen p-mode correction has little effect beyond that. Due to finer bin sizes, the CDFs do show that the exact distribution of exposure times is shuffled around somewhat, though the effect is again small (and largely confined to telescope/instrument/precision combinations that skew to shorter exposure times). In all cases, there is a “tail” of stars that have relatively long exposure times, even for favorable telescope/instrument/precision combinations. For less favorable ones, this “tail” can mean that around half of all stars have exposure times of over two hours (and so are difficult to observe).

The distributions of observations are largely similar between different p-mode compensation methods, with the exception of the fixed 10-minute case for otherwise short exposure times (NEID, 3.5 m, 27 cm/s and NIRS, 11.88 m, 40 cm/s). For those two telescope/instrument/precision combinations, a long fixed p-mode timescale increases the exposure times for most of the stars, and causes a noticeable reduction in the number of observations.

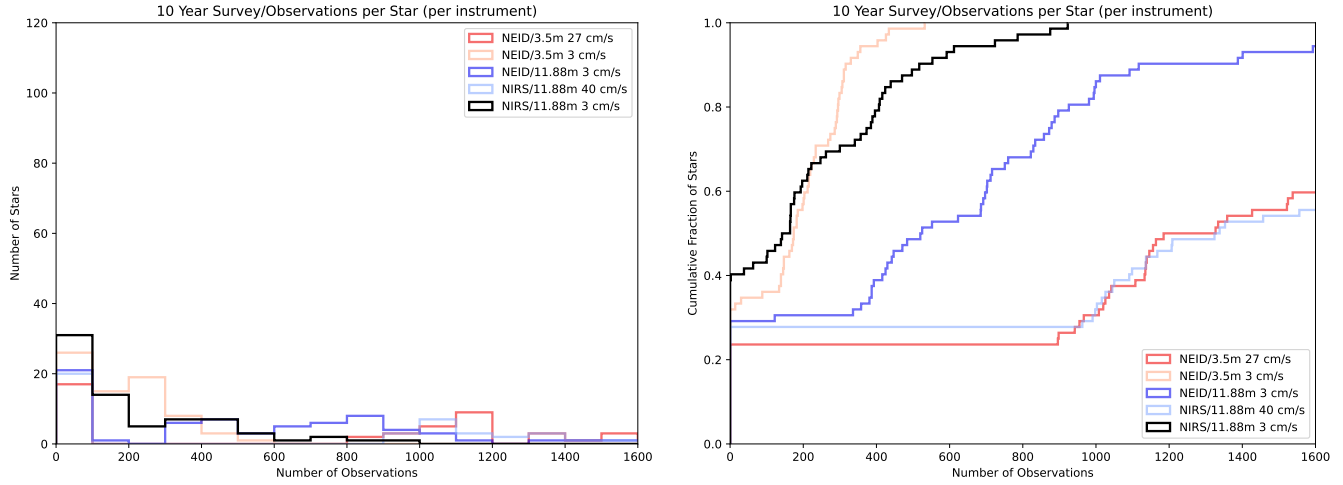


Figure 11. Histograms of total number of observations for the different telescope/instrument combinations as both PDFs (left) and CDFs (right). Differences between different architectures are quite obvious, though the ones between different p-mode compensation methods are subtle (and not apparent for the architectures with longer exposure times and fewer observations). Because of the details of the target list (both position and exposure times), between around 25 and 40% percent of the target stars are never observed.

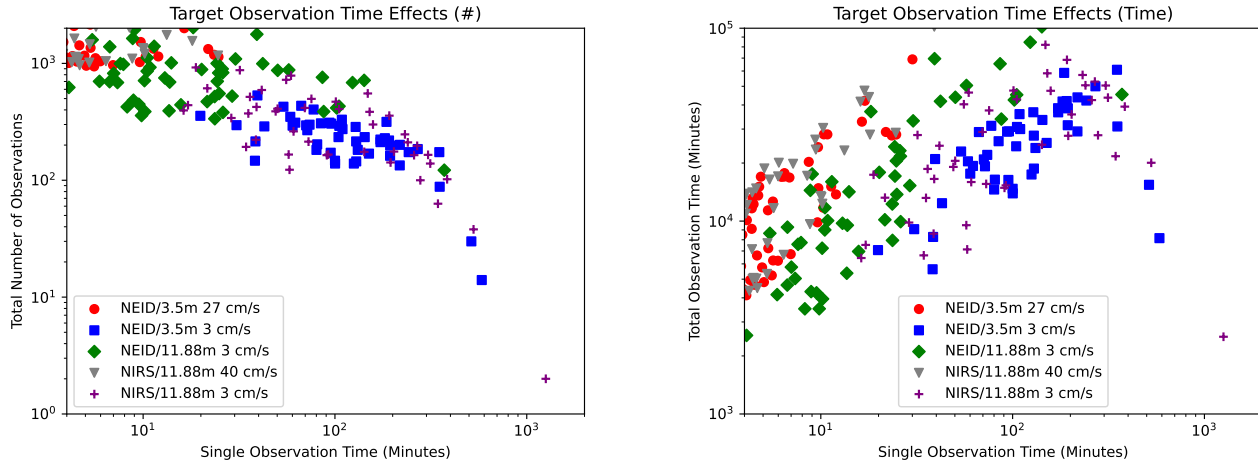


Figure 12. Total number of observations (left) and total time spent observing (right) for each star and telescope/instrument combination as a function of exposure time. Number of observations decrease slowly with increasing exposure time (while time spent on a given star increases) until around 300 minutes, and which point both rapidly decrease as the stars become increasingly impractical to observe.

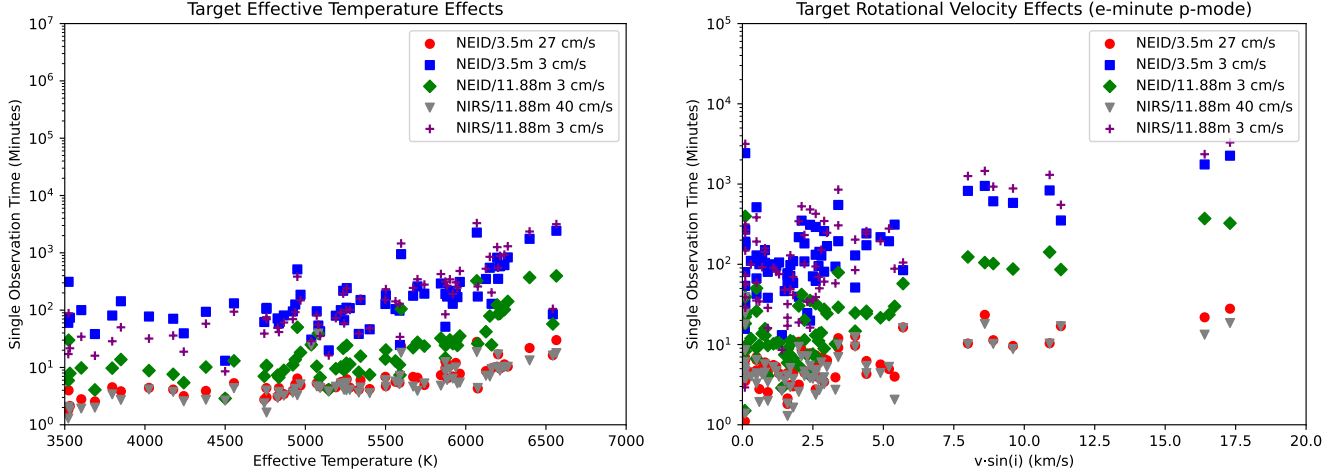


Figure 13. Exposure time as a function of effective temperature (left), and rotational velocity (right). This target list shows a clear trend of increasing observation difficulty for hotter stars, though choice of telescope, instrument, and target precision are more important for GKM stars. One star (Altair), is off the top-right corner of the vsini plot, due to its unphysically long exposure times at our desired precisions and having a rotational velocity of 211 km/s.

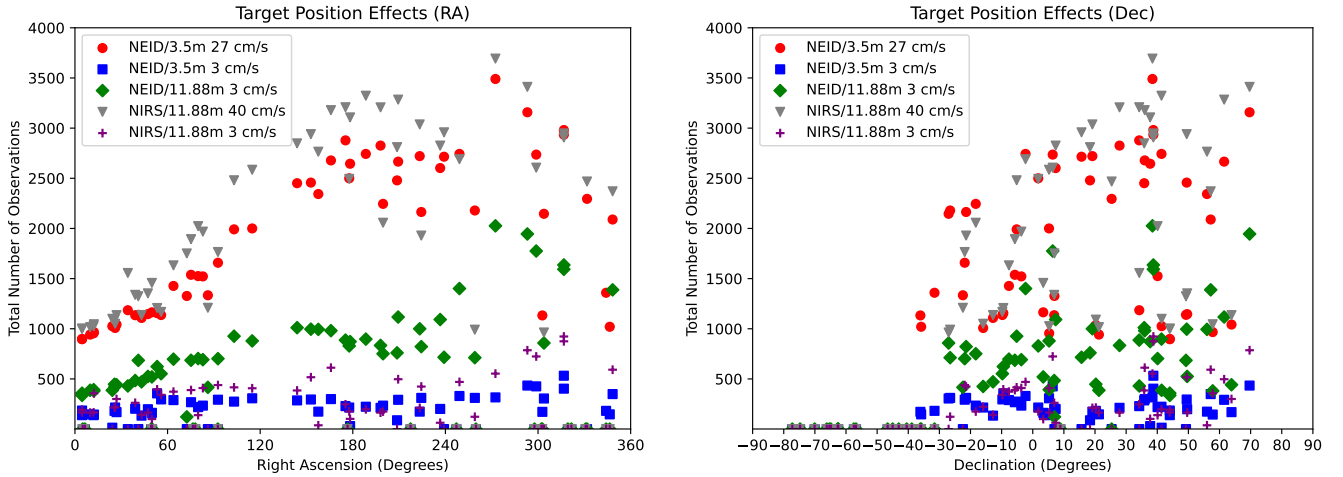


Figure 14. Total number of observations per star as a function of Right Ascension (top) and Declination (bottom). There is a clear trend in right ascension, we believe from a combination of night length and weather (though it is suppressed for longer exposure time telescope/instrument/precision combinations). That the peak corresponds with stars that have the longest time above the horizon in late summer (around 300-330 degrees) and not winter or early spring (when the weather is better and nights longer) is surprising. Declination does not show a clear trend, with number of observations per star being relatively flat north of about -40 degrees. Below that, stars are never observed.

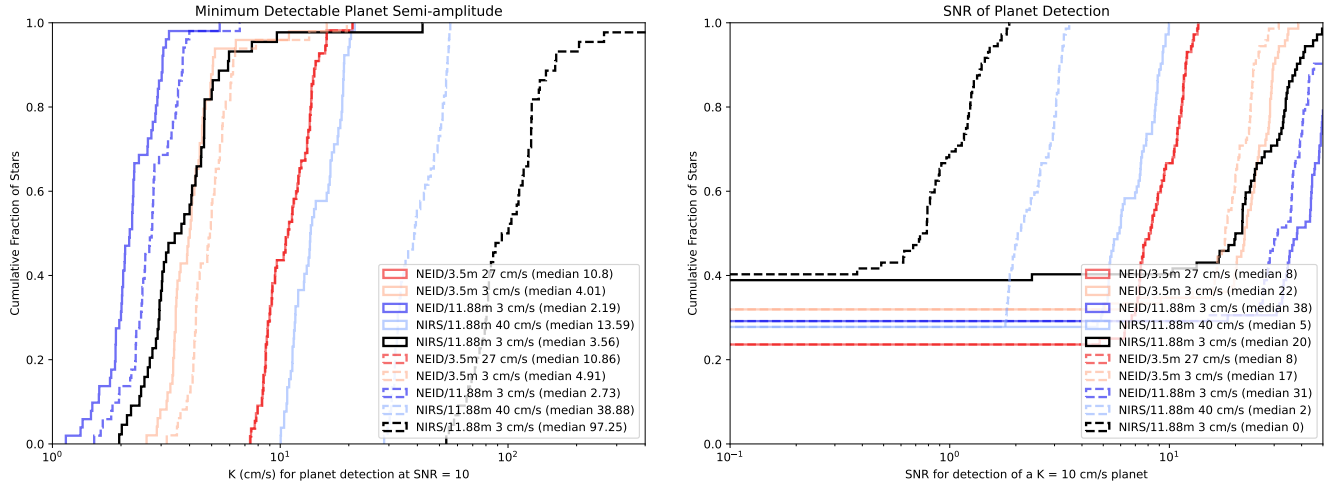


Figure 15. How our detection heuristic changes from no microtellurics (solid lines) to nominal microtelluric noise (dotted lines). **Left:** CDFs for the minimum detectable reflex velocity (K , in cm/s) for a planet at $\text{SNR} = 10$. **Right:** CDFs for the SNR for a detection of a $K = 10$ cm/s planet.

As our assumed noise is smaller than the instrument and photon noise sources in all but the most optimistic visible surveys, microtellurics have little effect. In contrast, this noise source dominates over all others in the NIR (being far larger than the instrument or photon components, even in the most pessimistic cases), and must be better accounted for if this wavelength range is to be useful in the EPRV era.

8. RESULTS (EPRV TARGET LIST)

To avoid redundancy, only the results using the surface gravity/effective temperature variable p-mode correction are shown.

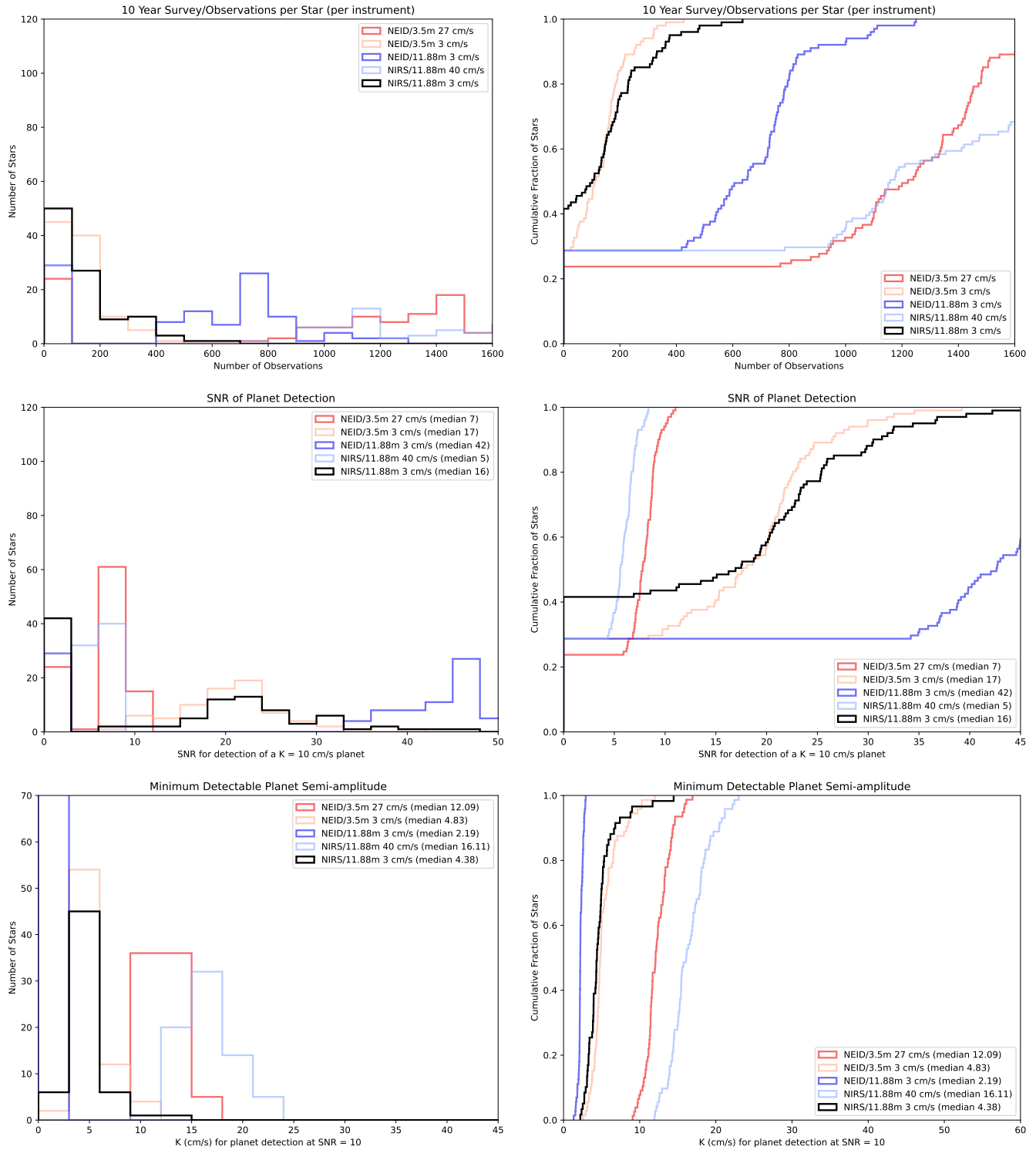


Figure 16. Histograms/PDFs (left) and CDFs (right) of the number of observations (top), SNR of a nominal 10 cm/s planet detection (middle), and minimum detectable reflex velocity k of a nominal SNR = 10 planet detection (bottom).

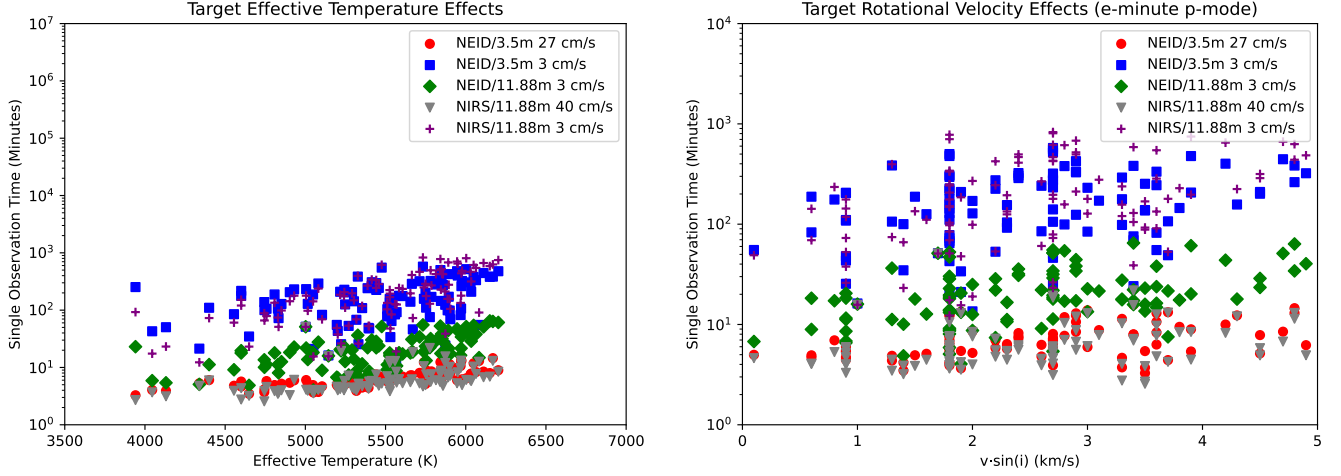


Figure 17. Exposure time as a function of effective temperature (left), and rotational velocity (right). This target list shows a clear trend of increasing observation difficulty for hotter stars, though choice of telescope, instrument, and target precision are more important for GKM stars. There is no clear trend in exposure time for $v \sin i$, possible due to all stars in this sample being slow rotators.

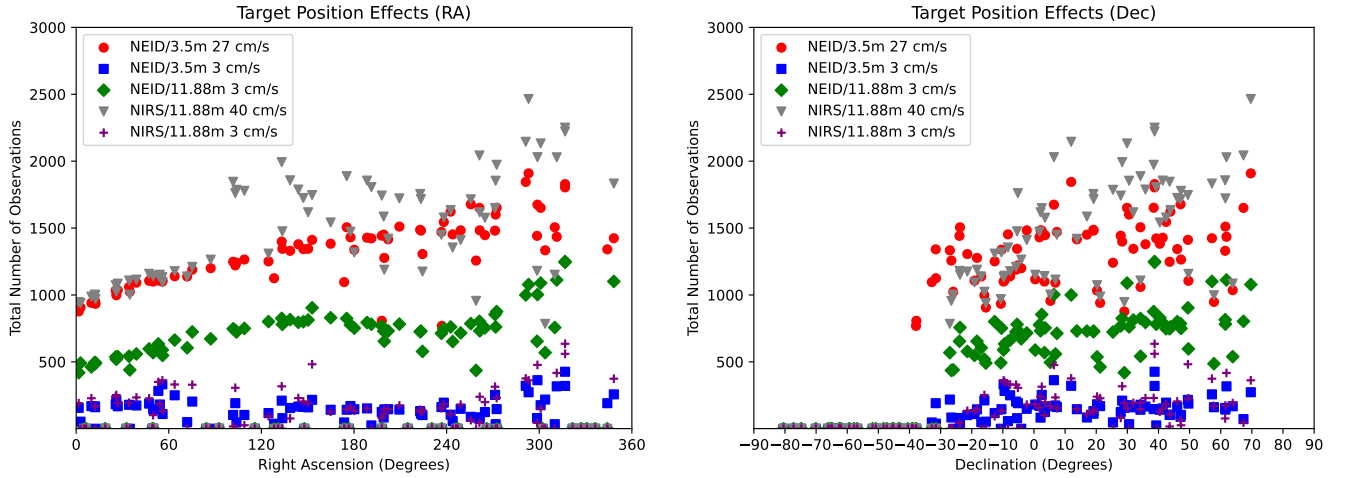


Figure 18. Total number of observations per star as a function of Right Ascension (left) and Declination (right). There is a clear trend in right ascension, we believe from a combination of night length and weather (though it is suppressed for longer exposure time telescope/instrument/precision combinations). That the peak corresponds with stars that have the longest time above the horizon in late summer (300-330 degrees) and not winter/early spring (when the weather is better and nights longer) is surprising. Declination does not show a clear trend, with number of observations per star being relatively flat north of about -40 degrees. Below that, stars are never observed.

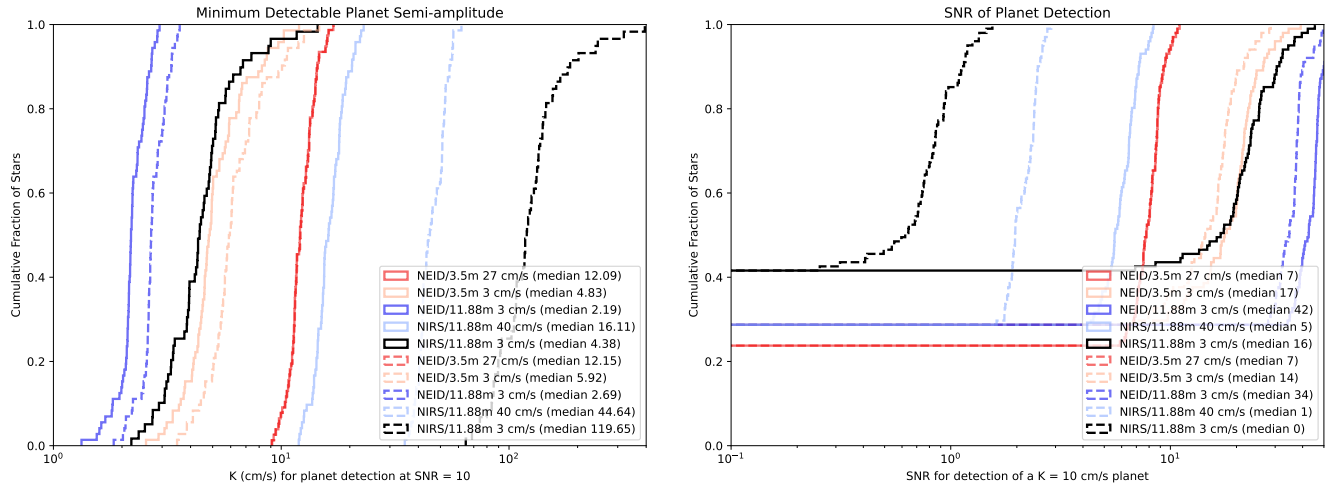


Figure 19. How our detection heuristic changes from no microtellurics (solid lines) to nominal microtelluric noise (dotted lines). **Left:** CDFs for the minimum detectable reflex velocity (K , in cm/s) for a planet at SNR = 10. **Right:** CDFs for the SNR for a detection of a $K = 10$ cm/s planet.

As our assumed noise is smaller than the instrument and photon noise sources in all but the most optimistic visible surveys, microtellurics have little effect. In contrast, this noise source dominates over all others in the NIR (being far larger than the instrument or photon components, even in the most pessimistic cases), and must be better accounted for if this wavelength range is to be useful in the EPRV era.

9. DISCUSSION

9.1. Exposure Time Considerations

Exposure time is an incomplete proxy for ease of observations, with other factors (discussed below) also being relevant. Difficult targets receive fewer exposures, though total time allocated to observing them only falls off when they become almost unobservable. The boundary between difficult and impossible to observe can be fuzzy for actual observations (until one reaches exposure times that are unphysically long), so our exposure time calculator makes no attempt to distinguish these.

Our exposure time calculator can, depending on inputs, generate arbitrarily long exposure times. We do not consider this a problem because: there is no clear cutoff for what makes a star impractical to observe, and the relative times are still useful as figures of merit. Depending on the survey goals, it is possible that they will want to: accept lower precision, tolerate long exposures, or drop the target entirely. We did not impose any limits on what times we accept in our simulations because we both wanted to get a feel for what was impractical within our assumptions, and our code gracefully deals with lists containing unobservable targets.

9.2. Comparisons to Other Exposure Time Calculators

Herein we compare our ETC considerations and results with some that are used for planning purposes at actual observatories, including one with one of our nominal instruments. As these sorts of ETCs are for planning out approximate time allocation needed, we expect that while results will approximately correlate, they will not be exact. Different systems are optimized for different types of targets, depending on typical observatory usage. Additional features that are subjects of ongoing research (eg: stellar activity) cannot be a-priori described to high detail because we do not yet know them in high detail.

9.2.1. ESPRESSO ETC

ESPRESSO is an existing EPRV instrument on the VLT at Paranal. Its exposure time calculator (Boffin et al. 2024) is available on the web⁶, and herein we compare the results.

This ETC has a large variety of spectral models, though there is a focus on giant stars and non-blackbody emission. For stars, they use a grid of atmospheric models, with options for their instruments, differing sky conditions, and single vs four telescope observing programs. The calculator is somewhat more focused on faint/low surface brightness (eg: extragalactic) sources, with the inclusion of sky brightness, with limited options in terms of sun-like stars. Though like us they gloss over line effects in the IR. It is well designed for planning with individual targets and specific dates, though the web interface would be a hassle for preparing for a large survey.

For the purposes of trends across spectra type, we look at exposures for a limited subset of stars:

| Spectra Type | S/N | RV precision (m/s) |
|--------------|---------|--------------------|
| G0 | 151.882 | 0.4 |
| G2V | 152.606 | 0.39 |
| K2V | 153.587 | 0.39 |
| K7V | 155.971 | 0.38 |
| M2V | 150.353 | 0.4 |

⁶ <https://www.eso.org/observing/etc/bin/gen/form?INS.NAME=ESPRESSO+INS.MODE=spectro>

There is a similar pattern (at least for constant V-mag) of getting consistent RV precision for a given exposure time across a fairly wide spectra type range. Using their most optimistic Precipitable Water Vapor, seeing, and Moon illumination figures and at the same airmass as we did.

We do not perform other comparisons, given the differences in what our ETCs focus on.

9.2.2. NEID ETC

NEID’s ETC is available both in web interface and downloadable forms⁷ for observation planning. It is more tightly focused on stellar RVs (in-line with the telescope/instrument’s tighter focus). They use a pre-computed grid of stellar models at various effective temperatures, and return precision based on that effective temperature and v-mag. Importantly, they reject any target/precision combination that would have a single observation time longer than 3600 seconds, so our comparisons focus on the lower precision/shorter exposure time end. We specifically look at both synthetic stars for overall trends (9.2.2), and a direct comparison of our target lists (9.2.2).

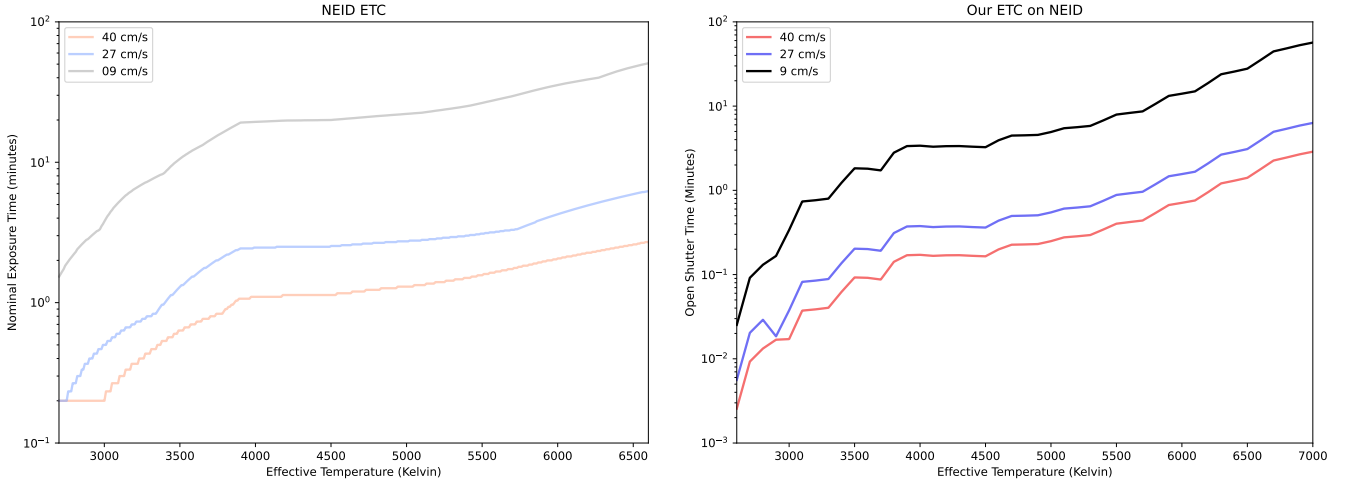


Figure 20. **Left:** Nominal exposure times at 3 RV precisions on NEID for synthetic stars that have an apparent V-magnitude of 4.83 as a function of effective temperature (so an unrealistic approximately constant luminosity, thus showing RV information content for a more or less constant number of photons as a function of temperature). The values are calculated with NEID’s official ETC over their modeled range (2700 to 6300 K). Lower values are ”better” (higher precision). **Right:** Equivalent synthetic stars stars (apparent magnitude 4.83, constant vsini, metallicity, and log(g), but with varying effective temperature) with exposure times calculated by our ETC. Both show similar trends, though the exact times are offset from each-other by about an order of magnitude. Given that none of these stars are especially real, such an offset is not concerning.

Our ETC approximately agrees with NEID’s, though there are significant differences in details, potentially resulting in a factor of several longer or shorter exposure time. We believe that this is from our considering additional stellar parameters, while also using comparatively simplified atmospheric and instrumental parameters. Given that the spread of exposure times overlap and our surveys all use target lists with a range of exposure times, these differences do not constitute a problem for

⁷ https://bitbucket.org/erik_timmermann_noao/neid-etc/src/master/

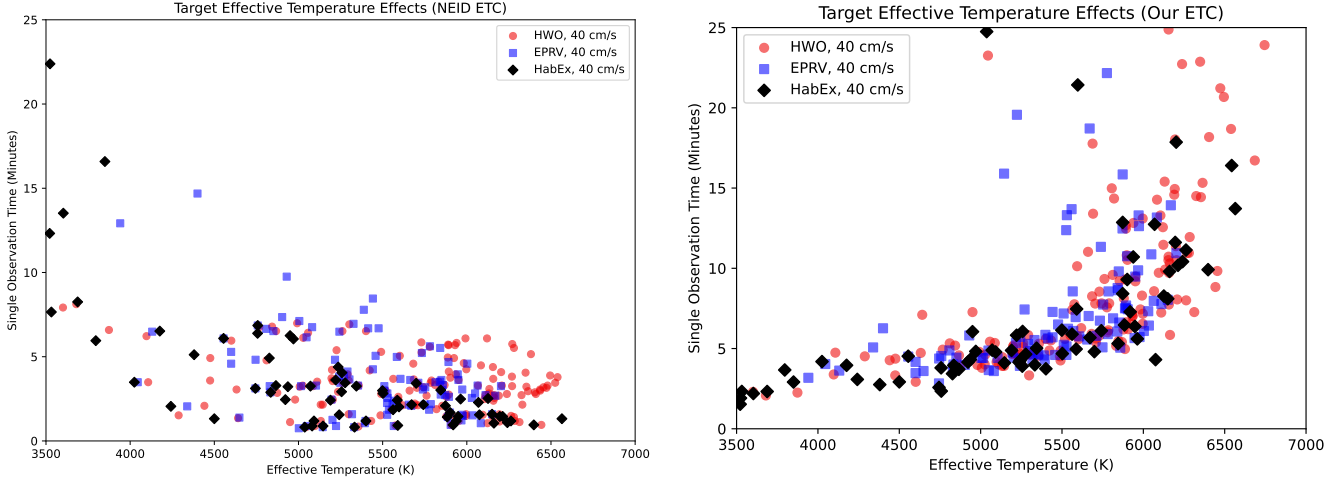


Figure 21. Left: Exposure times for the stars in our 3 target lists for a nominal single exposure at 40 cm/s, using the NEID ETC. Stars with exposure times longer than one hour are not shown. Depending on the target list, there can be a trend towards shorter exposures for hotter stars, but this is not always the case and it is relatively flat for stars hotter than around 4500-5000 K. If one wanted to choose a target list with a specific exposure time cutoff, they could do so while having stars across a broad temperature range. **Right:** The same target lists at the same scale are shown with our own exposure calculator. The higher “floor” in our times is from our p-mode compensation, and the upwards scatter at high temperatures is from increased vsini.

our general conclusions on survey parameters and viability. They can, however, greatly affect the achievable sensitivity for any specific star. Simulations that consider those additional features may be needed to more tightly define targets, especially for specific (as opposed to our generic) instruments.

9.3. *Dispatch Scheduler considerations*

Exposure times, stellar positions, site weather, and how targets are chosen all affect observation counts. Our time since last-observed weighting minimizes RA shadowing issues, so target spacing is not an overly large concern.

More generally, the dispatch scheduler deals relatively well with distributing observations between different targets, getting as many observations for each target as possible, and dealing gracefully with targets being difficult to observe. This combination of “good enough” and being computationally cheap is why we do not look at other weighting options, or more complicated algorithms such as [Garcia-Piquer et al. \(2017\)](#)

The “Traveling Telescope Problem” ([Handley et al. 2024a](#)) and associated slew concerns are primarily for the short exposure limit. The sorts of exposure times that we have here (including with the p-mode compensation) suggest that we would have fewer observations per hour/per night than they would. However, our assumed slew times are intentionally conservative, so work such as this could improve upon our assumptions.

Exploring how much of an improvement is possible with these sorts of methods, and if they present other limitations would be an avenue for future research.

9.4. Target Weighting

Number of observations per star were looked at for weighting schemes based on hour angle and/or time since last observation (with minimum delays between observations of 0.5, 1, 2, 4, 8, 16, and 32 hours considered). Variants on relative weighting strength were not otherwise attempted. Due to the difficulties in comparing histograms, the mean, median, and standard deviation of the number of observations were considered as figures of merit.

In general, target selection (number of stars, exposure times, location) had larger effects than the algorithms explored. Which weighting algorithm was more effective also depended on the target list. A small/widely separated one did best with pure hour angle. The full list contains a number of stars that can interfere with each-other, so a method of upweighting that prevents that is preferred.

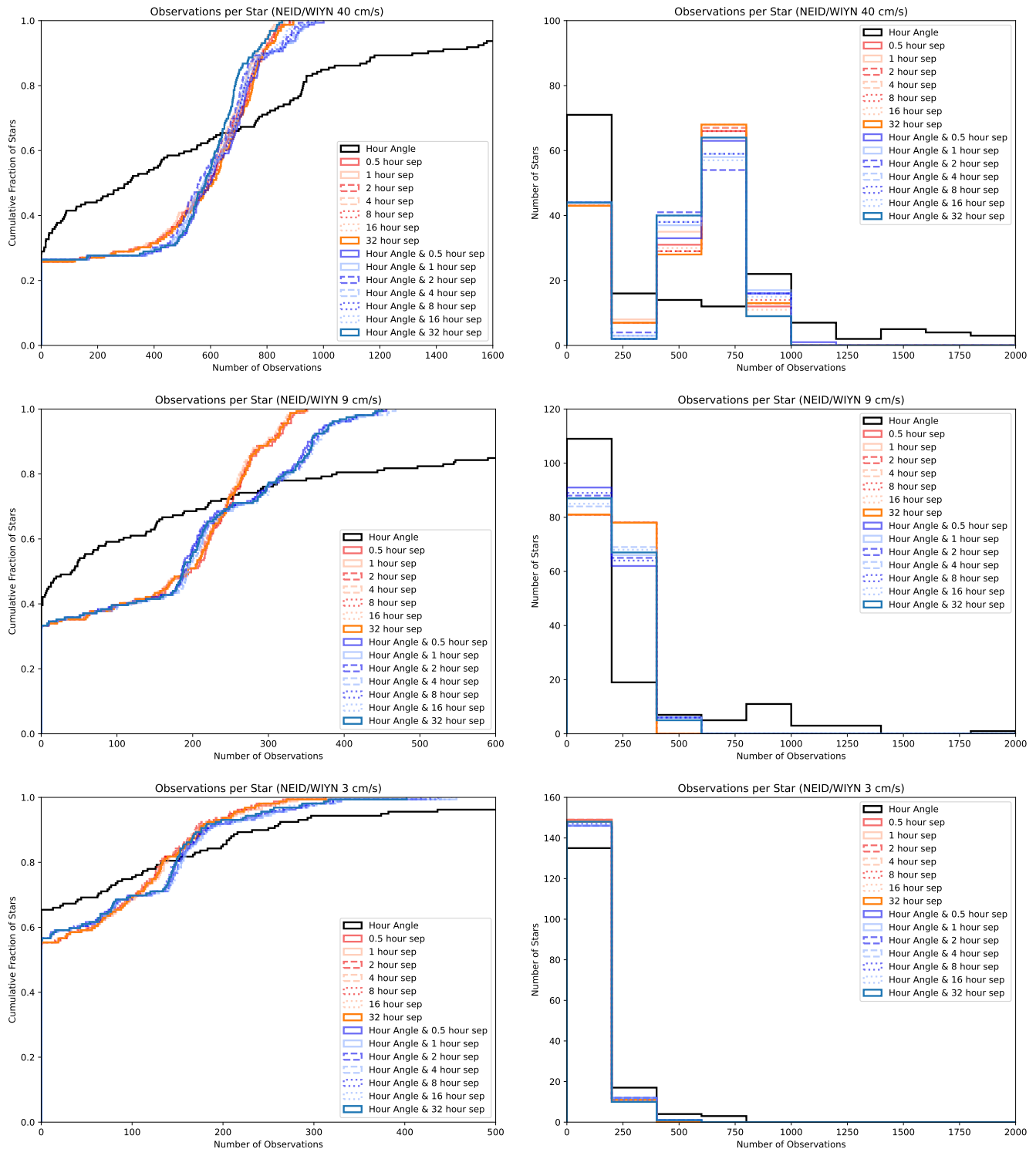


Figure 22. PDFs (left), and CDFs (right) of all stars in the HWO target list for different precisions and a large variety of observation weighting strategies. Here we look at 3 main strategies: a simplistic hour-angle weighting, a time since last observation weighting (do not observe the object again at all within the time limit, and then ramp up the weighting), and a combined hour-angle and time since last observation weighting. The last two are relatively similar (especially for shorter exposure times), but we find that the combined weighting is the “best”.

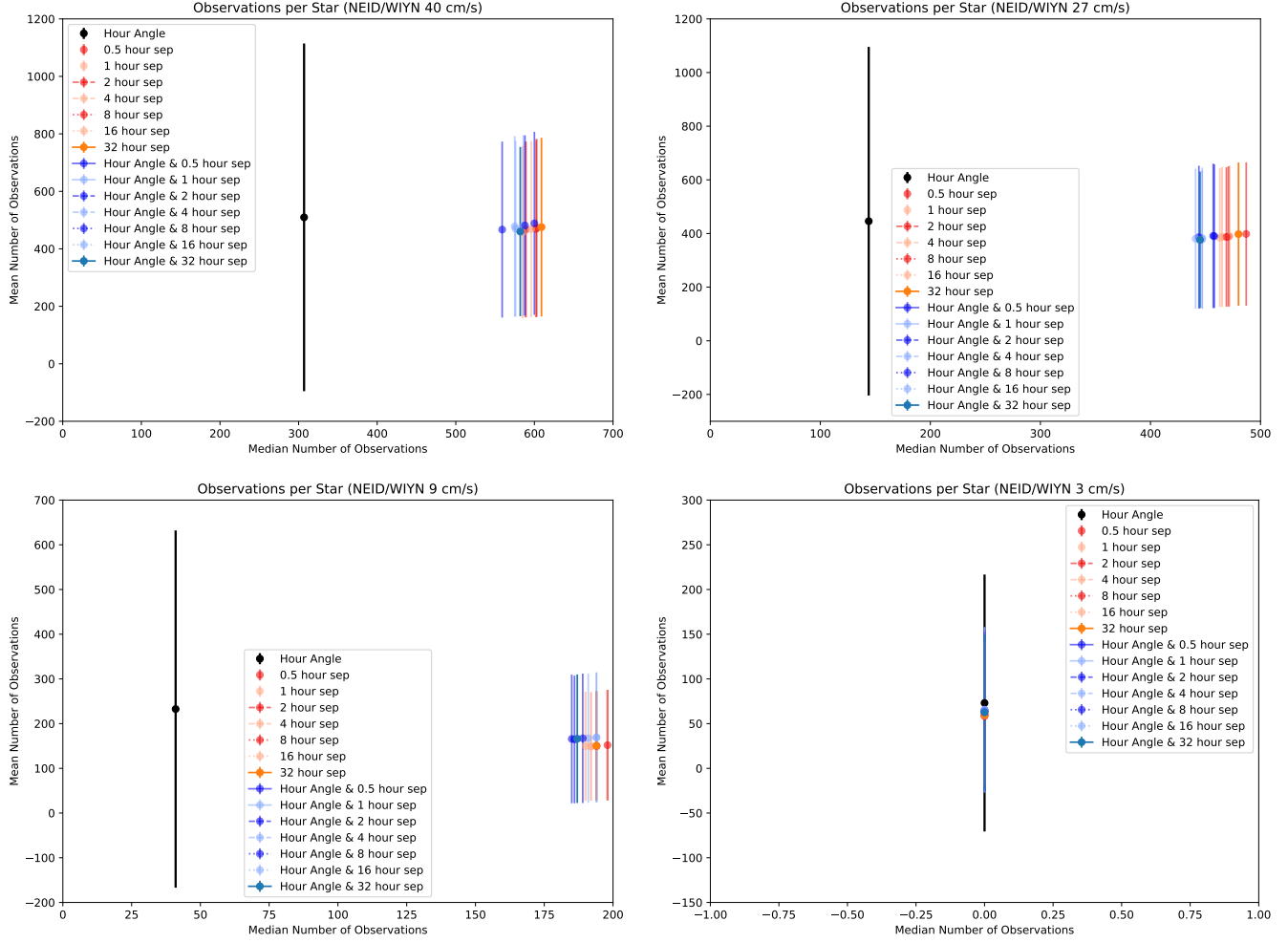


Figure 23. Plots of the distribution of results for different precisions and a variety of weighting strategies. We compare median (x-axis) with mean (y-axis) and standard deviation (error bars). Here we look at 3 main strategies: a simplistic hour-angle weighting, a time since last observation weighting (do not observe the object again at all within the time limit, and then ramp up the weighting), and a combined hour-angle and time since last observation weighting. The last two are relatively similar (especially for shorter exposure times), and unlike the broader distributions, it looks like pure time since last observation is the “best”. Notably, for 3 cm/s, we are unable to observe the majority of the stars, hence a median of 0.

9.5. Do the different *P*-mode calculation methods affect yields?

The minimum timescale as determined by the *p*-mode oscillations has a large effect on exposure times only when other factors combine to result in very short exposures. They set a floor which within our constraints is only reached for relatively low precisions, favorable stars, and/or large telescopes.

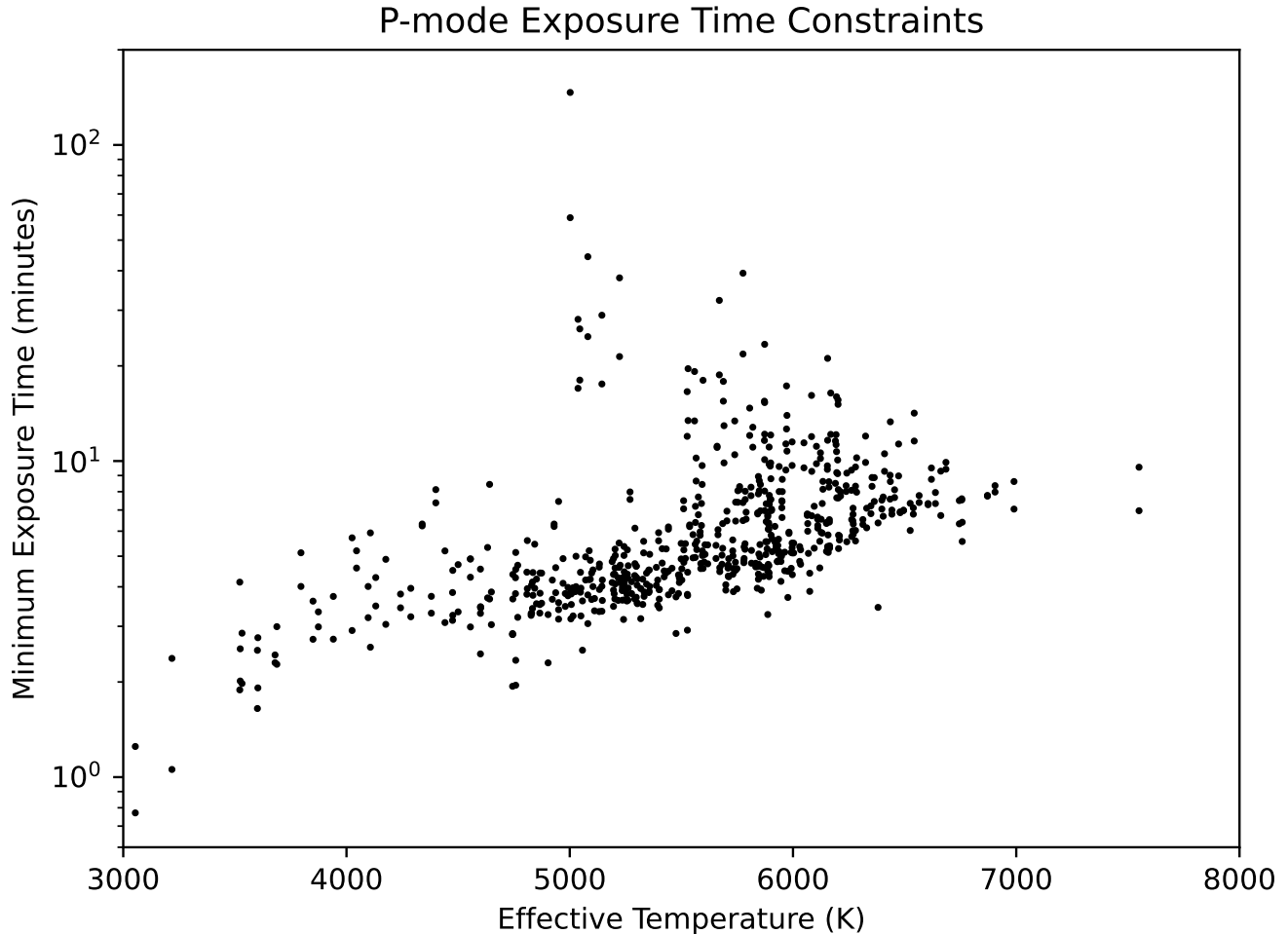


Figure 24. All minimum p-mode times across all target lists as a function of effective temperature. Most are shorter than 5 minutes and the vast majority are shorter than 10. The remainder include stars that a direct observation mission may wish to pass over (eg: subgiants).

While both the mass-radius and gravity-temperature methods look similar, it is worthwhile to check to see if they are producing different distributions. To do this, we performed K-S tests on our distributions of exposure times, observation counts, and K/SNR heuristics. We first look at the extremes of short and long exposure time cases that we simulated, and then at the shortest ones within the preferred instrument/telescope/sensitivity combinations.

While we do see some differences, the shortest exposure time we simulated is a “noncanonical” telescope/instrument combination with a telescope size and instrument sensitivity that is at the edge of the trade-space. The shortest exposure time combination that is “canonical” (27 cm/s NEID analog on a 3.5 m telescope) shows a somewhat different pattern.

Any physically-motivated p-mode comparison appears to have similar effects on survey results for a realistic survey, though differences are possible in the short-exposure limit. If a survey spends a relatively long time on each star, then the method will not matter.

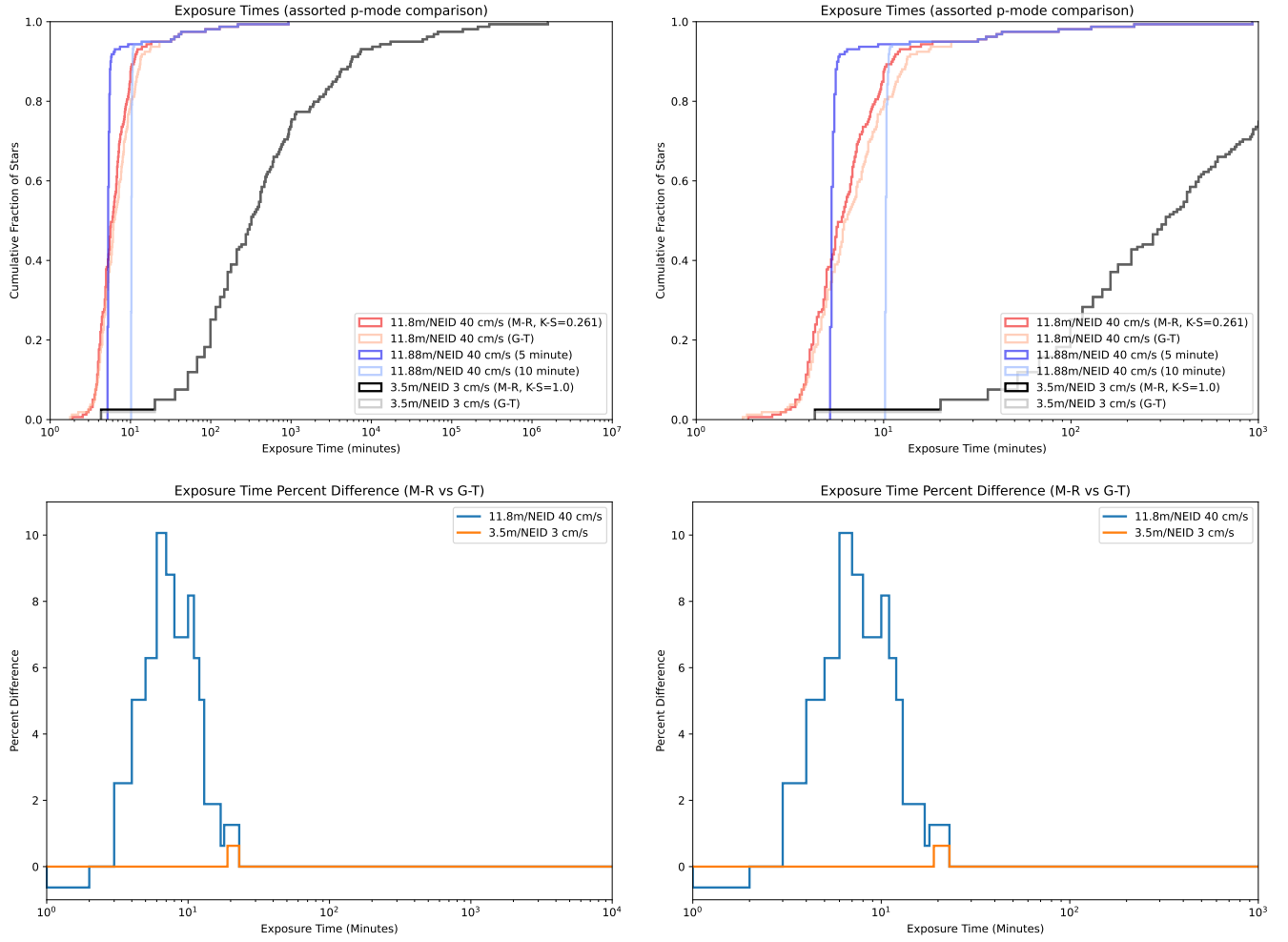


Figure 25. Comparison of the exposure time distributions for four kinds of p-mode oscillation compensation measures: fixed 5-minute versus fixed 10-minute versus two kinds of variable (mass-radius and effective temperature-surface gravity). The telescope/precision combinations that otherwise give the shortest exposures (11.8 m and 40 cm/s) and longest exposures (3.5 m and 3 cm/s) using NEID are used. In the CDF graphs (**top**), the p-values for a null result between the two variable exposure modes (the mass-radius and temperature-gravity using distributions are the same) are given in the figure keys. The **bottom** panels show 'percent difference' between the two variable p-mode timescale distributions. The two fixed timescale distributions are not considered, as they are different by inspection (though overlap in some ways with the other distributions). The K-S test does not show these two distributions as statistically different (the p-value for the 40 cm/s case is >0.05 , and for the 3 cm/s case is around 1).

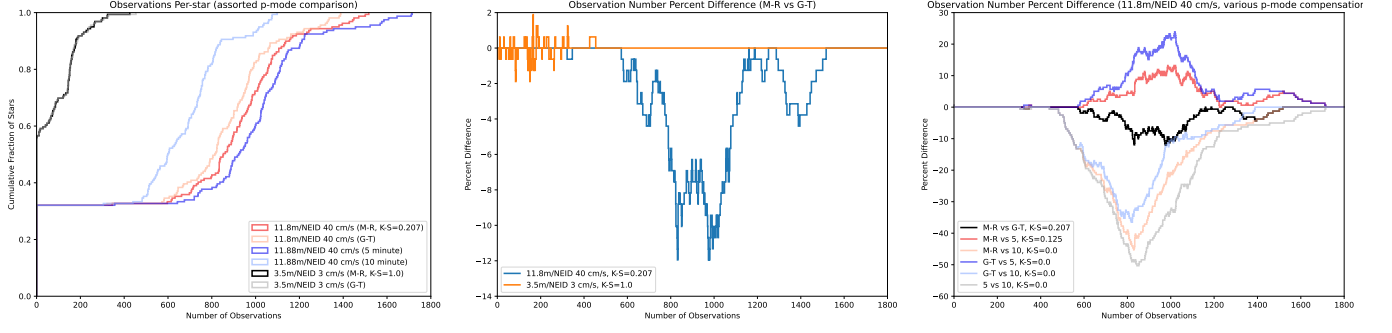


Figure 26. Comparison of the same 6 datasets in observation distribution. The left graph is the CDF of the distributions, while the middle is the percent difference for the two variable p-modes, and the right is the percent difference between all combinations for the short exposure time case. Notably unlike the exposure time distributions, these are in some cases distinguishable from each-other.

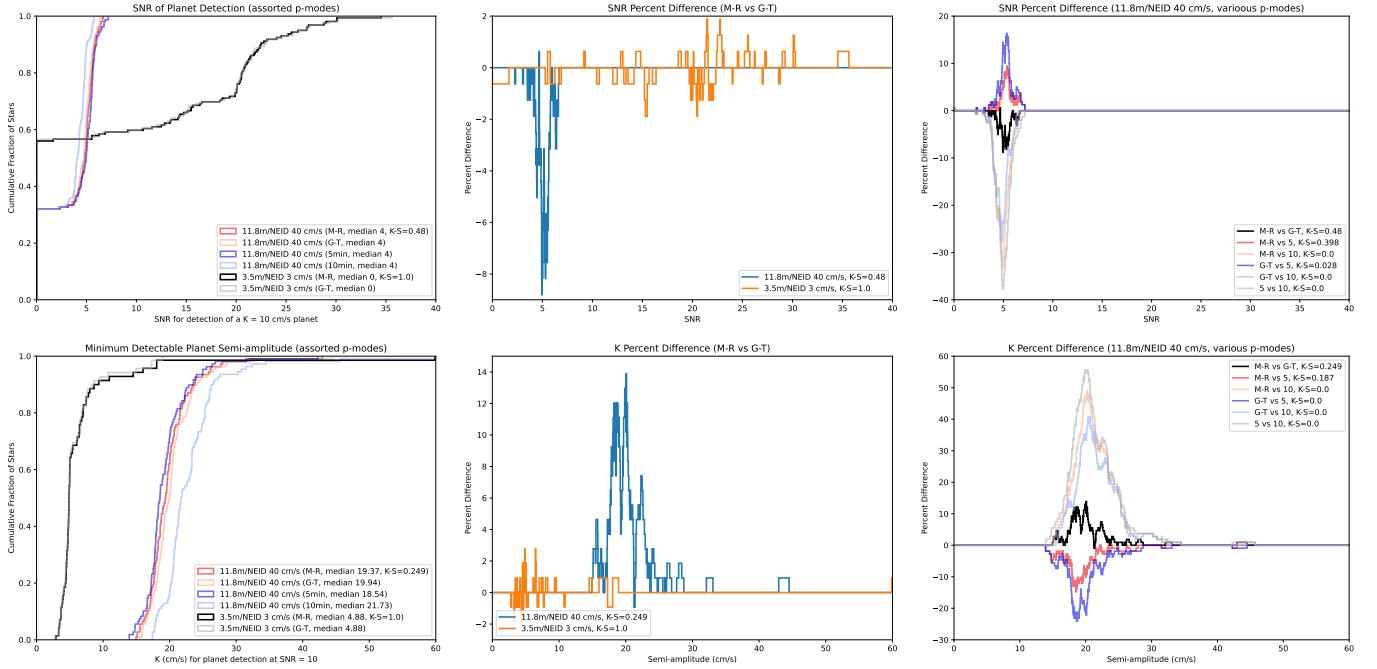


Figure 27. Comparison of the same 6 datasets in their distributions for our K/SNR detection heuristic (semi-amplitude sensitivity at an SNR of 10 is top, SNR for a fixed semi-amplitude of 10 cm/s is bottom). The left graphs are the CDF of the distributions, while the middle are the percent difference for the two variable p-modes, and the right is the percent difference between all combinations for the short exposure time case. Using a cutoff of $p < 0.05$, we find that the two variable p-mode calculations cannot be distinguished from each-other, nor the mass-radius method from a 5-minute cutoff. All others can be, as can usually be seen by offsets in their CDFs (which appear as peaks/troughs in the percent difference).

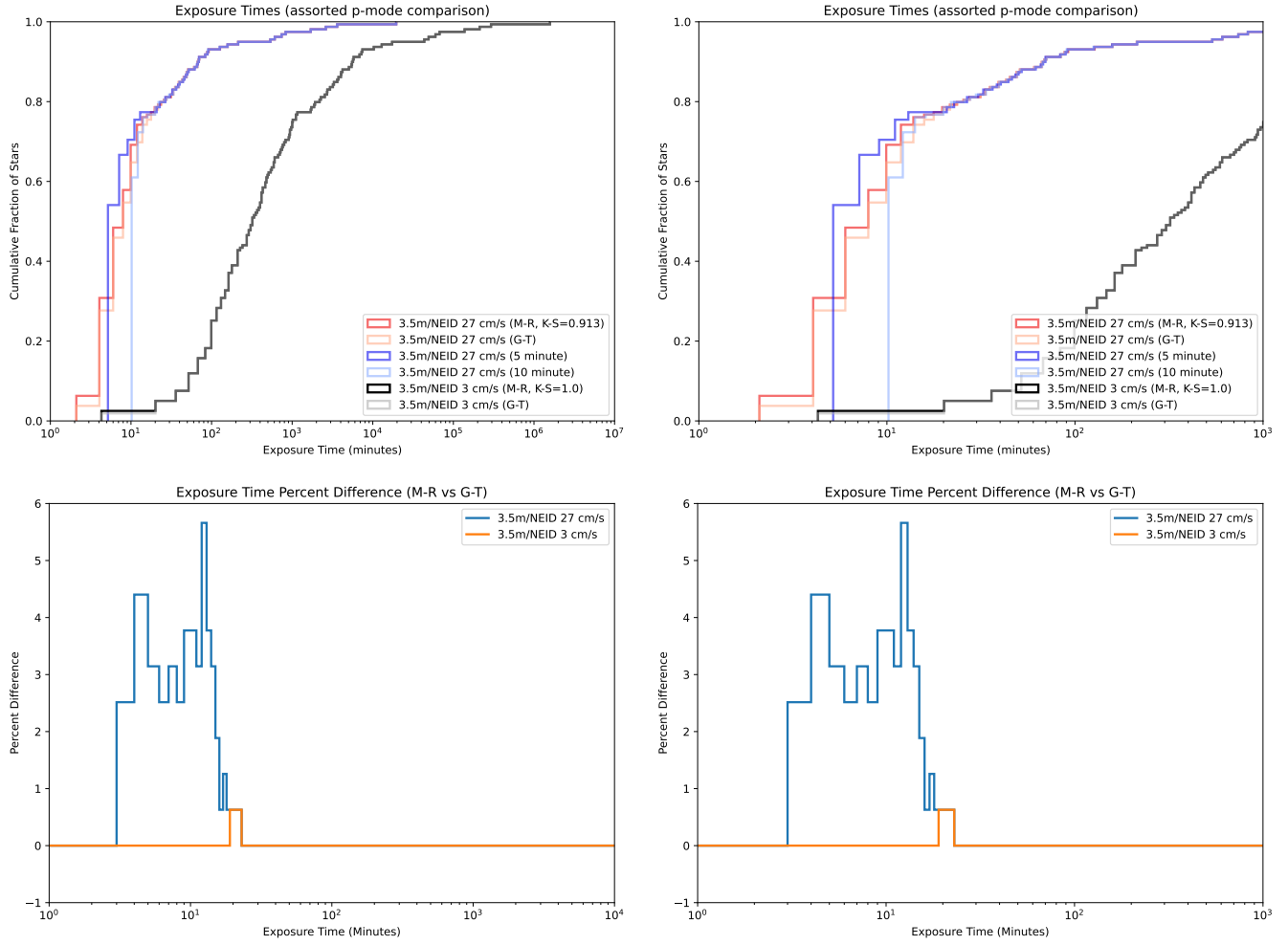


Figure 28. Comparison of the exposure time distributions for four kinds of p-mode oscillation compensation measures: fixed 5-minute versus fixed 10-minute versus two kinds of variable (mass-radius and effective temperature-surface gravity). The telescope/precision combinations that are “canonical” and give the shortest exposures (3.5 m and 27 cm/s) and longest exposures (3.5 m and 3 cm/s) using NEID are used. In the CDF graphs (**top**), the p-values for a null result between the two variable exposure modes (the mass-radius and temperature-gravity using distributions are the same) are given in the figure keys. The **bottom** panels show ‘percent difference’ between the two variable p-mode timescale distributions. The two fixed timescale distributions are not considered, as they are different by inspection (though overlap in some ways with the other distributions). The K-S test does not show these two distributions as statistically different (with p-values of near to or exactly 1).

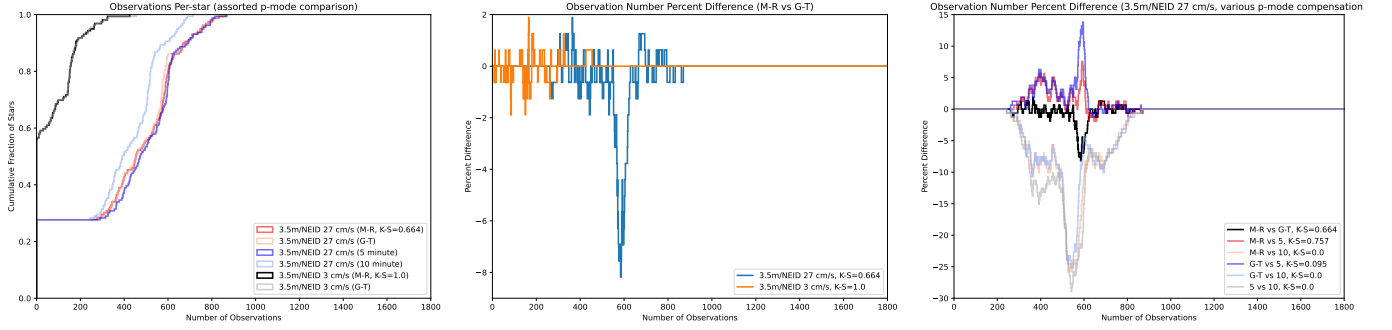


Figure 29. Comparison of the same 6 datasets in observation distribution. The left graph is the CDF of the distributions, while the middle is the percent difference for the two variable p-modes, and the right is the percent difference between all combinations for the short exposure time case. The variable p-modes remain indistinguishable from each-other, though the fixed 5-minute is somewhat distinguishable from either. The fixed 10-minute p-mode has a statistically significant and visible offset distribution from the rest.

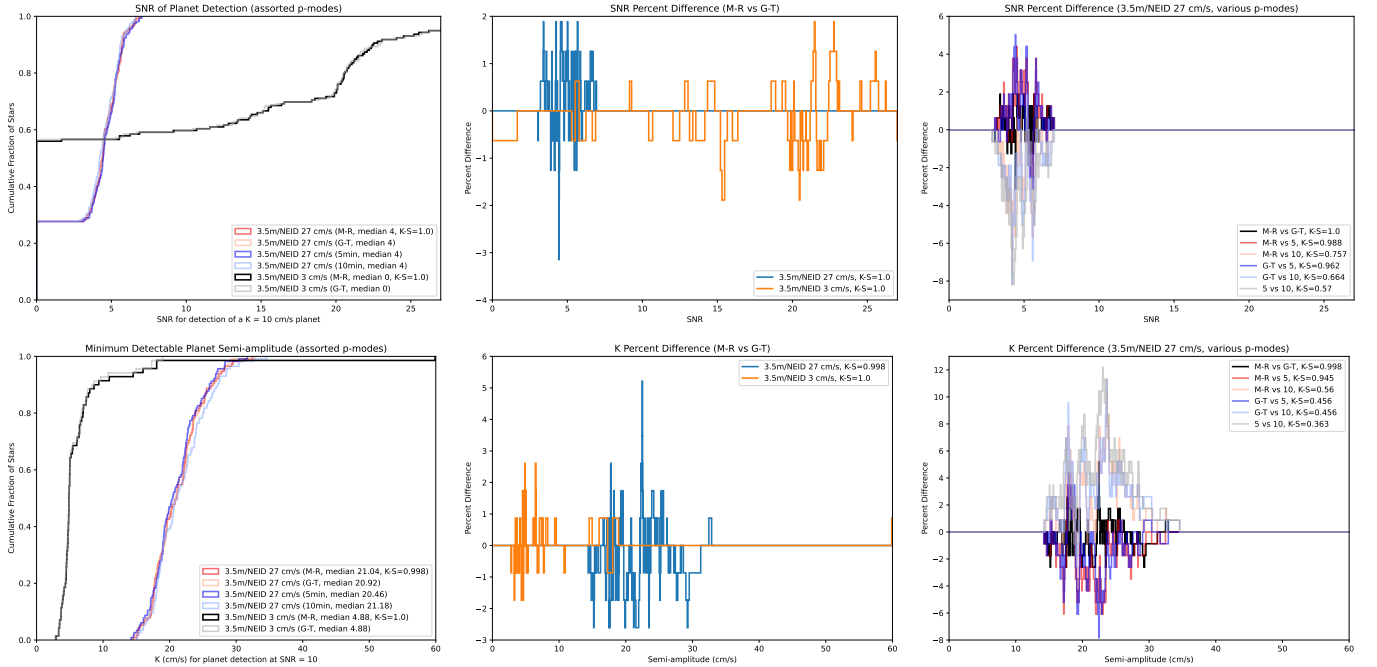


Figure 30. Comparison of the same 6 datasets in their distributions for our K/SNR detection heuristic (semi-amplitude sensitivity at an SNR of 10 is top, SNR for a fixed semi-amplitude of 10 cm/s is bottom). The left graphs are the CDF of the distributions, while the middle are the percent difference for the two variable p-modes, and the right is the percent difference between all combinations for the short exposure time case. Using a cutoff of $p < 0.05$, we find no p-mode compensation method is different from any other. This is supported by the overlapping CDFs.

Exact details of stellar position are likely to be interacting with the changes in exposure times and/or differences in the weather used (we do not use the same seed for each run), to cause the differences in the observation distributions. That the flat 5-minute floor produces similar results to the variable minimum observation times is potentially interesting, though it may be a result of our assumptions (which give the sun a 300 second, or a 322 second minimum, depending on the method used).

Our detection heuristic has tighter offsets between the CDFs, though due to their near-vertical portion, these are often statistically significant. These suggest that depending on how it is performed, our simulations may have systematic errors from p-mode compensation of up to some tens of percent.

All of these differences are minimized for telescope/instrument/precision combinations that push exposure times longer, and can render them of minor importance for some and no importance for a few of them.

9.6. Target List Comparison/Target Star Selection

The choice of target stars dramatically affects survey efficiency and efficacy, primarily through exposure time and positional constraints. While our code can deal with some difficult to observe stars, typically due to declination or exposure time, others are impossible to observe at the sorts of precisions necessary to find earth-analogs. Our stellar activity considerations do not greatly affect exposure times, so the variations here are primarily about the information content of spectra and raw number of photons.

While in principle our target list is a volume-limited sample, there are sufficiently many stars that selecting for “easier” ones remains a possibility. Since our most-disfavored stars (hotter ones) are relatively rare, this does not overly constrain us on number of targets. Focusing on “easier” stars may more subtly bias the survey, though it still reduces the time an eventual direct imaging survey needs to spend on detection/allows more focus on classification.

As we find that an optimistic declination cut does not present issues, this suggests that they should be chosen more on limiting the number of target stars (assuming that there are too many with short exposure times) than by constraints on observability.

Stars with limited numbers of observations would risk having alias issues. A more subtle aspect of our assumptions is that we want a high cadence to properly model stellar activity. While these simulations use a single site, weather losses (and potentially target list size) would introduce gaps could make this level of activity characterization impossible.

As we have multiple nominally optimized target lists, we can do a degree of comparison.

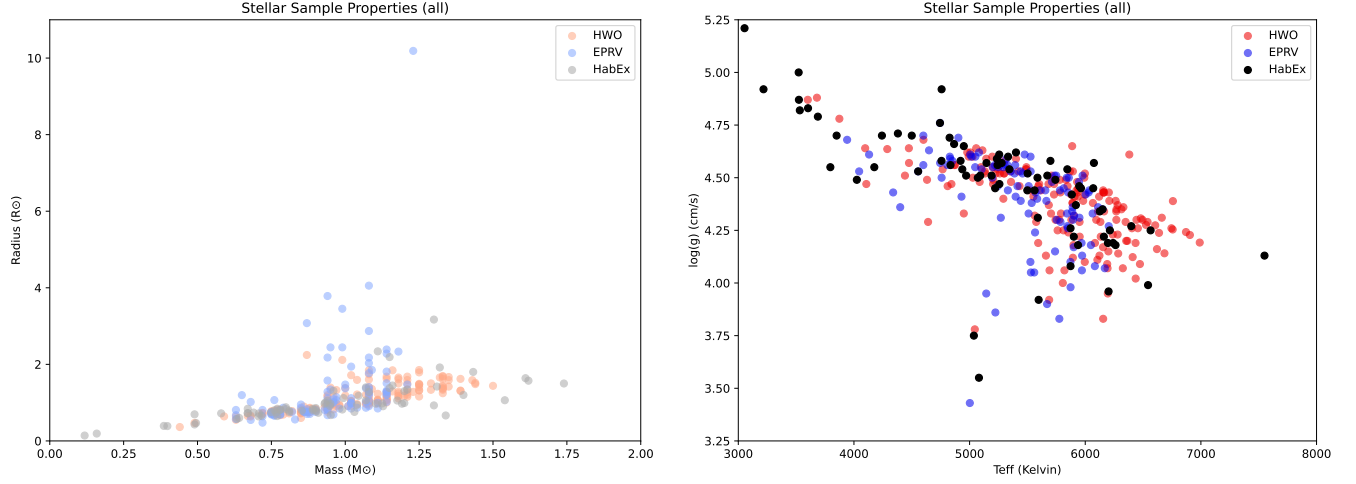


Figure 31. A comparison of our 3 target lists in the parameter spaces used for p-mode compensation.

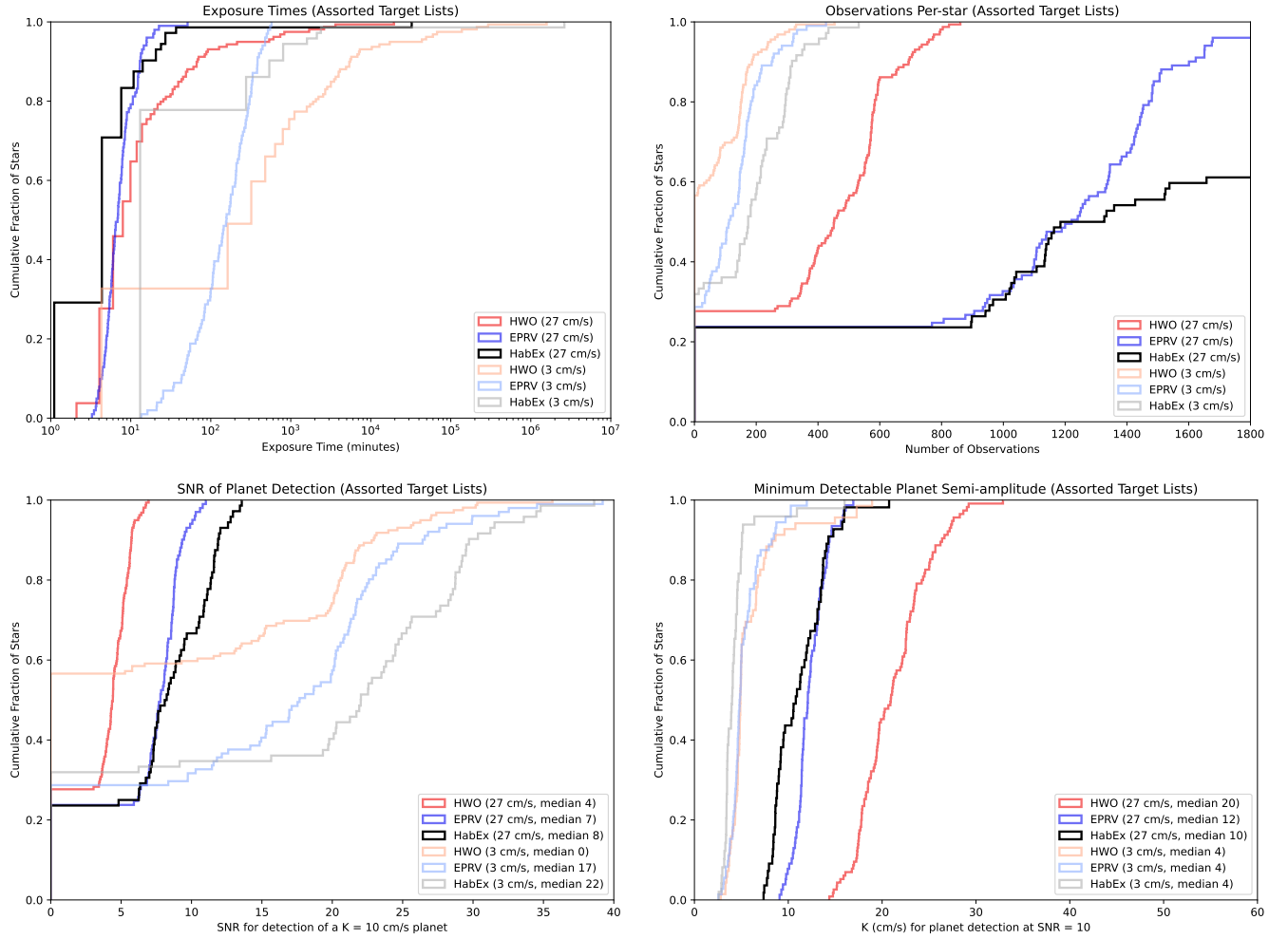


Figure 32. A comparison of our 3 target lists (HWO, EPRV, HabEx), for typical high and low precisions using the NEID spectrograph on a 3.5 m telescope. (**top:** CDFs of exposure times and observation counts, **bottom:** CDFs of our K /SNR detection heuristic).

The apparent differences are likely caused by these CDFs glossing over the differing sizes of the target lists, as well as the differing observability. The increased number of stars in general, and “good” stars in particular the HWO list (as compared with the HabEx and EPRV lists) means that observations are spread out over more stars, and everything gets measured to a lower precision.

While we do not quantify the value of target list size (aside from our detection heuristic), this suggests a limit to the target list length for a precursor survey, especially with the large number of observations required. If a survey is to be volume limited, it may need more or larger telescopes to get sufficient numbers.

If our primarily unmodeled noise sources are white noise (as our detection heuristic assumes), this does point to a smaller / more frequently observed target list as a way to compensate for noise sources that are otherwise larger than we consider.

9.7. Other/Uncompensated Noise

We do not do attempt to directly mitigate any noise beyond oscillations, likely resulting in significant reductions in ‘actual’ SNR values and higher minimum semi-amplitudes than are shown. (Though longer exposures also likely suffer less from granulation.) Using [Luhn et al. \(2023\)](#)’s results as a figure of merit, we expect reductions on the order of a factor of 3-6 for correlated noise, and 2 for white noise, for a total reduction in SNR of about 4-9x. There is a great deal of ongoing work to improve on stellar activity, including sun as a star observations. ([Rubenzahl et al. 2023](#); [Llama et al. 2024](#); [Ford et al. 2024](#); [Klein et al. 2024](#)) These suggest that a NEID-equivalent could find an Earth-analogue around a sun-analogue with on the order of 1000 observations, a number that we reach for many targets. Additional work to mitigate noise may be able to reduce these further, and more realistic simulations of both the noise sources and mitigations thereof would be work for a future paper.

Finally, we do not attempt to model telluric noise, assuming that it will be sufficiently small and/or there will be improvements in mitigation/modeling. Our nominal noise parameters suggest that this is a safe assumption in the visible, but not in the infrared (from their sizes relative to other noise sources). While upcoming EPRV observatories (and the nominal instruments we simulate) will have features like sky fibres, more work is needed.

10. CONCLUSIONS

We (re)introduce a series of codes for calculating exposure times/RV precision, taking into account some degree of atmospheric absorption and compensating for some stellar activity. We also (re)introduce codes for performing realistic dedicated surveys.

We consider multiple target weighting algorithms, settling on a combination of hour angle and time since last observation. Despite the simplicity, does a relatively good job of making use of the telescope and distributing observations among target stars, with results in line with real-world surveys.

We compare the code with existing exposure time calculators and find (results) broadly similar temperature trends. What parameters various ETCs consider varies enough that other comparisons are difficult, and suggest serious limits on their accuracy without careful per-site/instrument or per-target adjustments. However, our broad trends should be sufficient for “typical” targets.

The important of cadence/multiple sites is highlighted for avoiding poor detection strength from weather.

We have found that target star selection is important for reasons above and beyond stellar activity. eg: Slow-rotating nearby K-dwarfs are much easier to observe than many others. Early M-dwarfs

may also work well. G-dwarfs, while more difficult are doable. F and especially A stars are impractical to obtain our desired single measurement precision on. These effects are from: effective temperature being comparatively unimportant over a wide range, but reducing line quantity and increasing microturbulence for hotter stars, as well as increasing rotational velocities (especially past the Kraft Break).

Target star declination is important, though like effective temperature has a relatively broad range where stellar observations are similar in difficulty and number. Right ascension can also matter, though how much and which ones are “best” will vary with the site (from weather and length of night). Even for the “worst” right ascensions, a target list should have some stars, unless exposure times are so long that the list needs to have a minimum of targets.

While previous work showed that one can account for p-mode oscillations approximately (and that they don’t necessarily affect survey results), we show that we can also directly choose exposure times to minimize them. This does not present significant computational overhead or increase in survey difficulty, and so can “just” be done in future EPRV work.

We also show that the p-mode compensation method has little effect on exposure times (and therefore observation rates), outside of the large telescope/low precision limit. The physically based methods use related scaling methods and are centered at solar (5 minute) values, so this is unsurprising. An intentionally different method (10 minutes) does offset things, but again the effect is small and only relevant when exposure times are short (well below 10 minutes).

Finally, we find that telluric noise sources are presently manageable in the visible, but are show-stoppers in the NIR without additional corrections.

Software: [astropy](#) ([The Astropy Collaboration et al. 2018a](#)) ([The Astropy Collaboration et al. 2018b](#)) [numpy](#) ([Oliphant 2006](#)) [matplotlib](#) ([Hunter 2007](#))

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