Simulating Precursor Radial Velocity Surveys for Future Exoplanet Direct Imaging Missions

Patrick Newman[1], Peter Plavchan[1], Justin Crepp[2], Shannon Dulz[2], Chris Stark[3], Steven Kane[4]

[1]George Mason University, [2]Notre Dame, [3]Space Telescope Science Institute, [4]San Francisco State University

Survey, and exposure time/RV precision codes.

Motivation

Space based direct imaging exoplanet surveys proposed for the 2020s and 2030s (e.g.: WFIRST, HabEx, LUVOIR) are expected to be very expensive for the (high value) data that they will return. Observation time and therefore cost can be reduced by a factor of 2 to 10 if the telescopes can be aimed exclusively at known/imageable exoplanets, but first these planets must be found. Improvements in ground based spectrographs may make such pre-targeting possible with a radial velocity survey in the 2020s. The simulations here are being developed to determine if and to what extent such ground based surveys are worthwhile. At present, this is a proof of concept that a multi-year survey with a large telescope can provide a useful number of observations at useful precision.

Code Description

Our survey code uses the MINERVA scheduler as a starting point, which we have modified for our simulations. It performs a Monte Carlo simulation of an observing campaign, and includes a visualization script for the results. We take site location (latitude, longitude, altitude, weather), target properties (right ascension, declination, exposure time), survey duration, sun/moon position, and telescope properties (park position, slew speed, integration time, minimum altitude) into consideration. We output sun/rise set times, star rise/set times, star observation logs (altitude, azimuth, conditions), and general survey metadata.

Our radial velocity precision code uses an analytic model of astrophysical sources of uncertainty, given an input SNR and wavelength range (Beatty and Gaudi 2015). This model considers the effects of: Stellar spectrum (BT-Settl), spectrograph resolution, log(g), T_{eff}, metallicity, v·sin(i), and macroturbulence on RV signal. It does not consider granulation or starspots/faculae.

Wavelength range, precision, and observation length

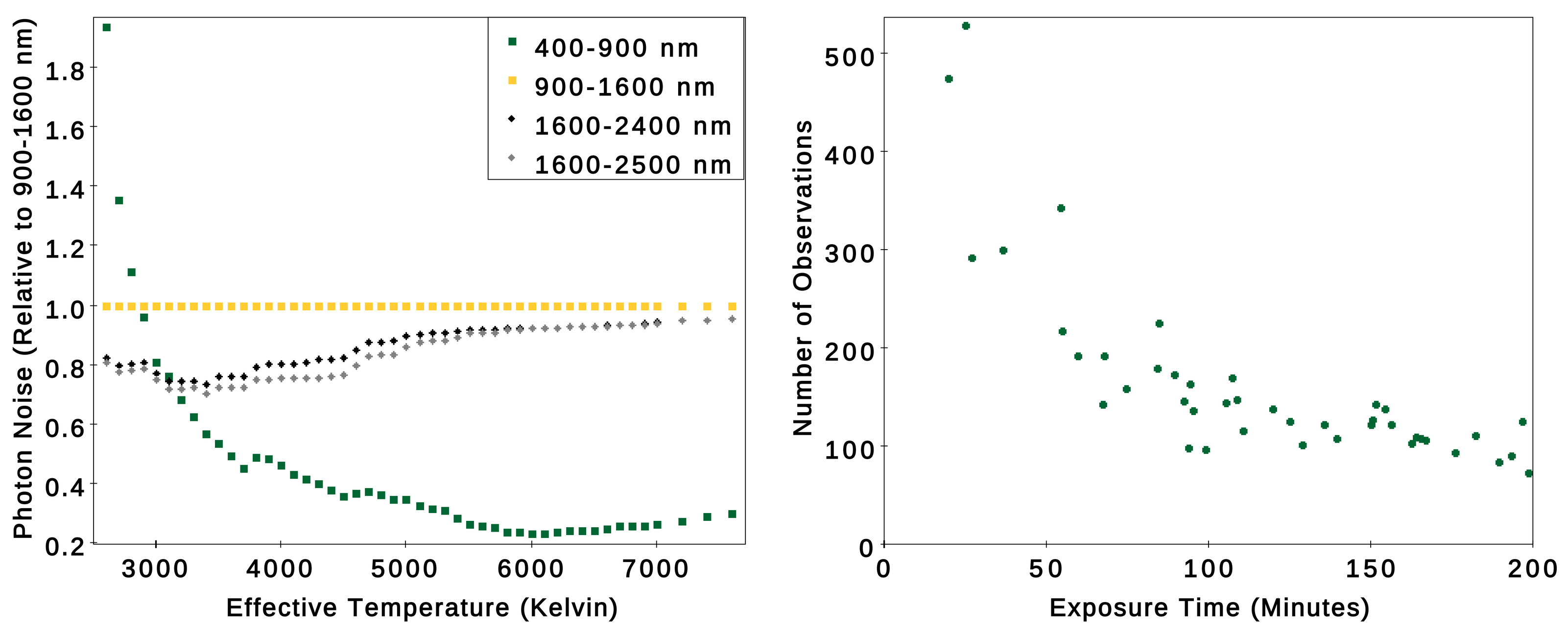


Figure: Left: Relative radial velocity precision verses stellar effective temperature in multiple wavelength ranges and in the ideal (no stellar or instrument noise) case.
Right: Exposure times and number of observations for a 3 cm/s survey of 42 FGK stars using the NEID instrument. An informal cutoff has been adopted as stars beyond 200 minutes are increasingly unobservable.

What to observe next?

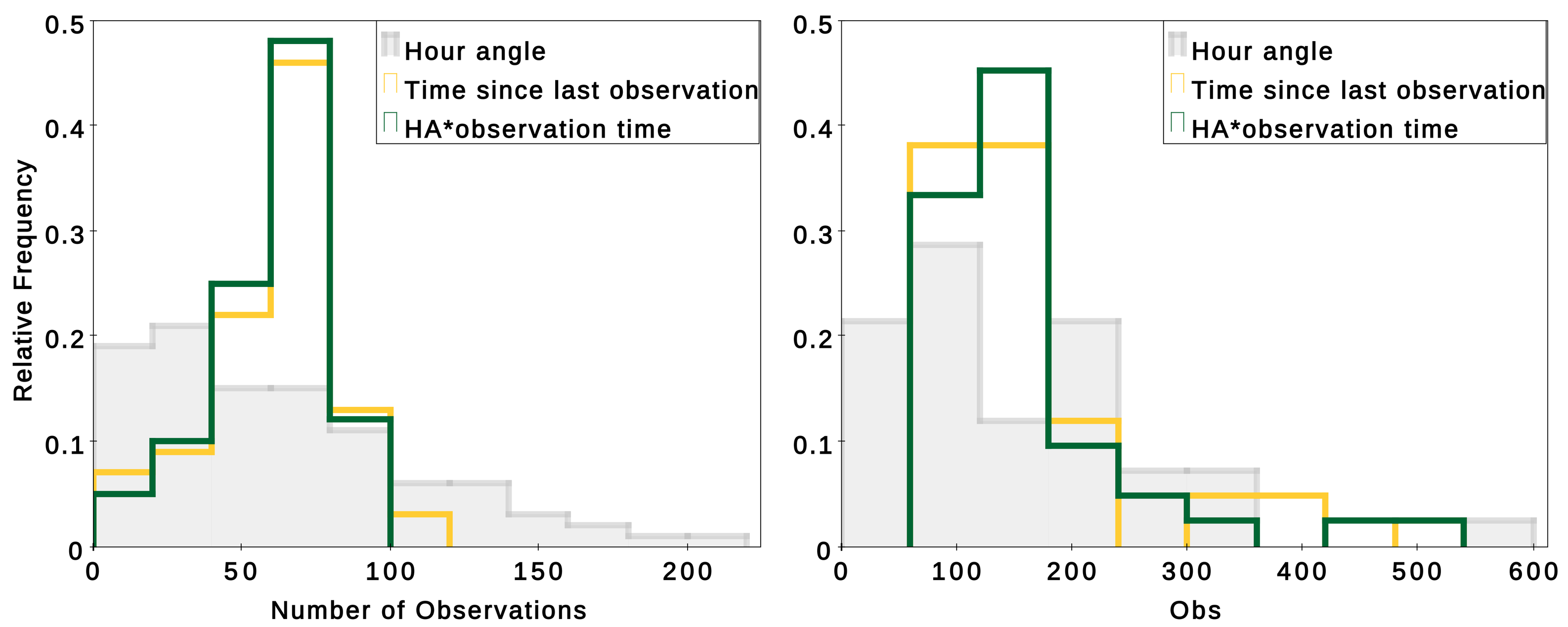


Figure: Left: Distribution of observation counts using multiple observing strategies for 100 stars with 60 minute exposure times over a 3 year survey. Narrower distributions preferred.
Right: The same strategies for 42 stars in a 3 cm/s 5 year survey.

Where are the best stars?

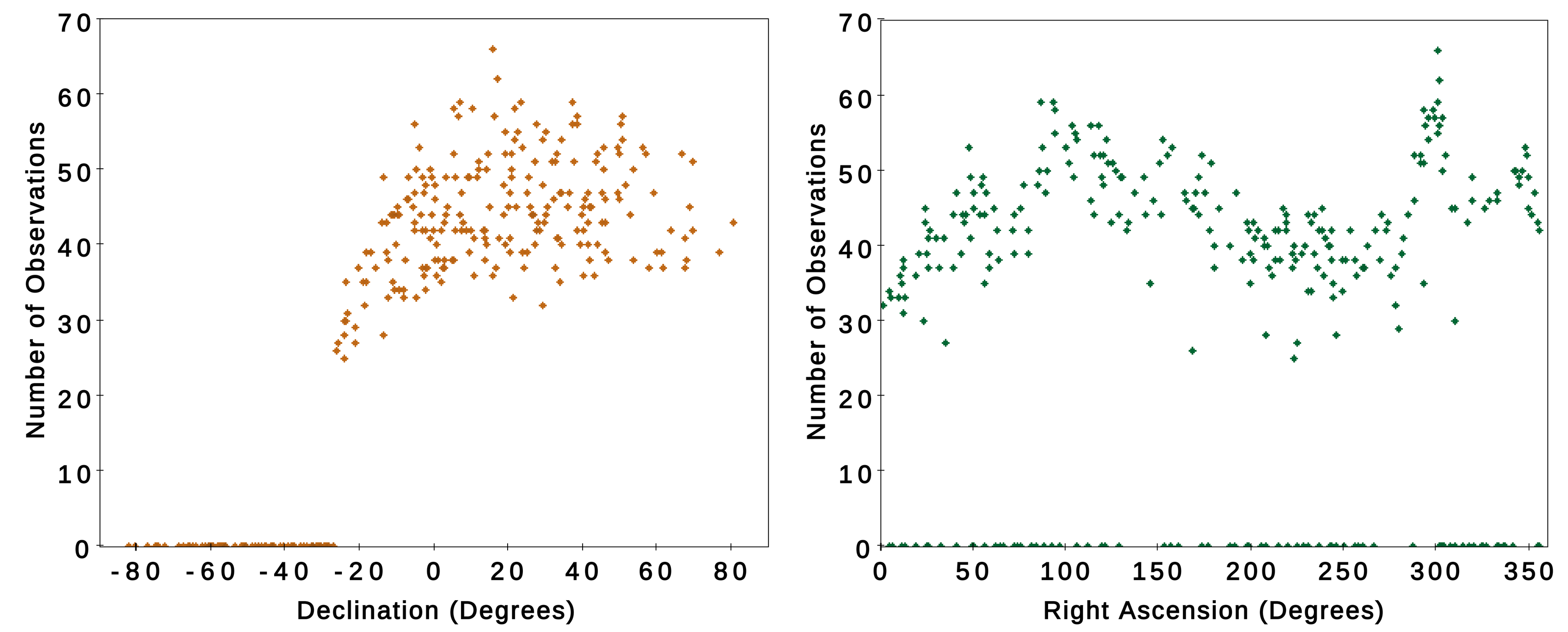


Figure: Distribution of observation counts for 312 stars with 60 minute observation times at the WIYN telescope over a 5 year run verses right ascension (right), and declination (left). The variation in observation count verses right ascension is from a combination of night length and weather conditions.

Representative stars

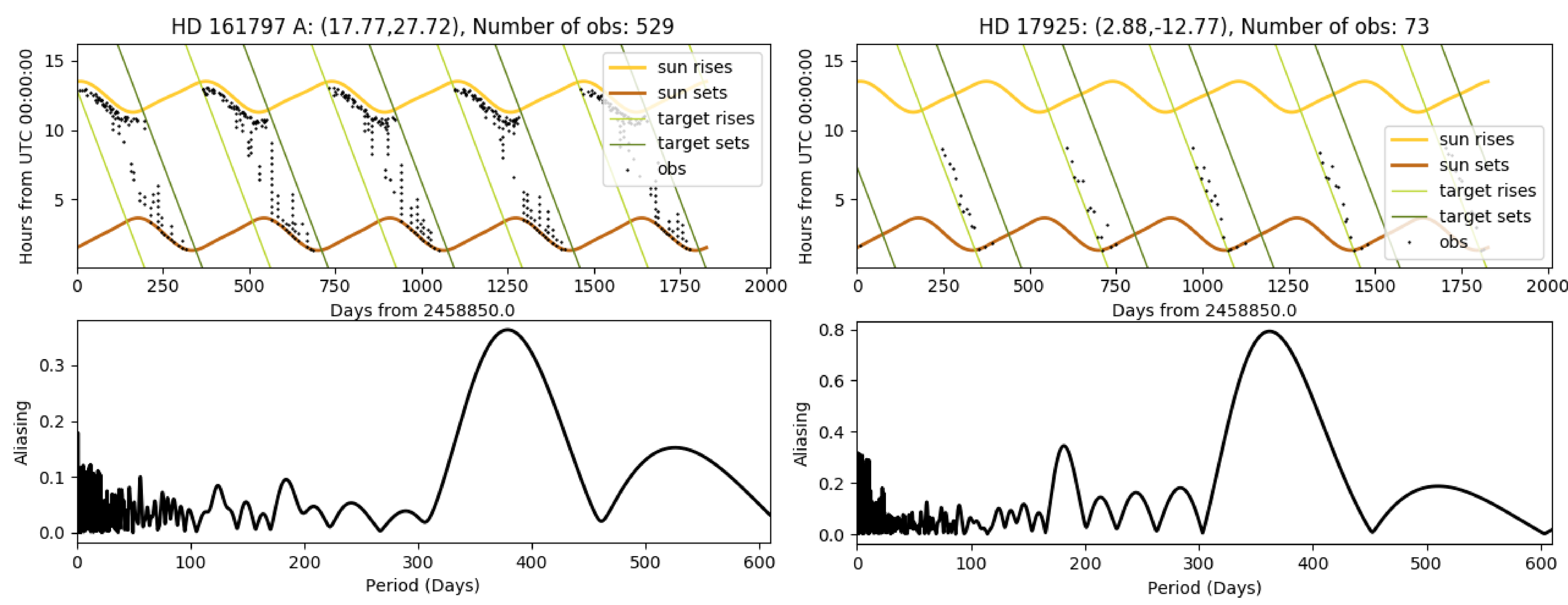


Figure: The stars with the most observations (right), and fewest observations (left) in the 3 cm/s 42 star survey. HD 161797A has a particularly favorable exposure time and declination, while HD 17925 is particularly unfavorable for both.

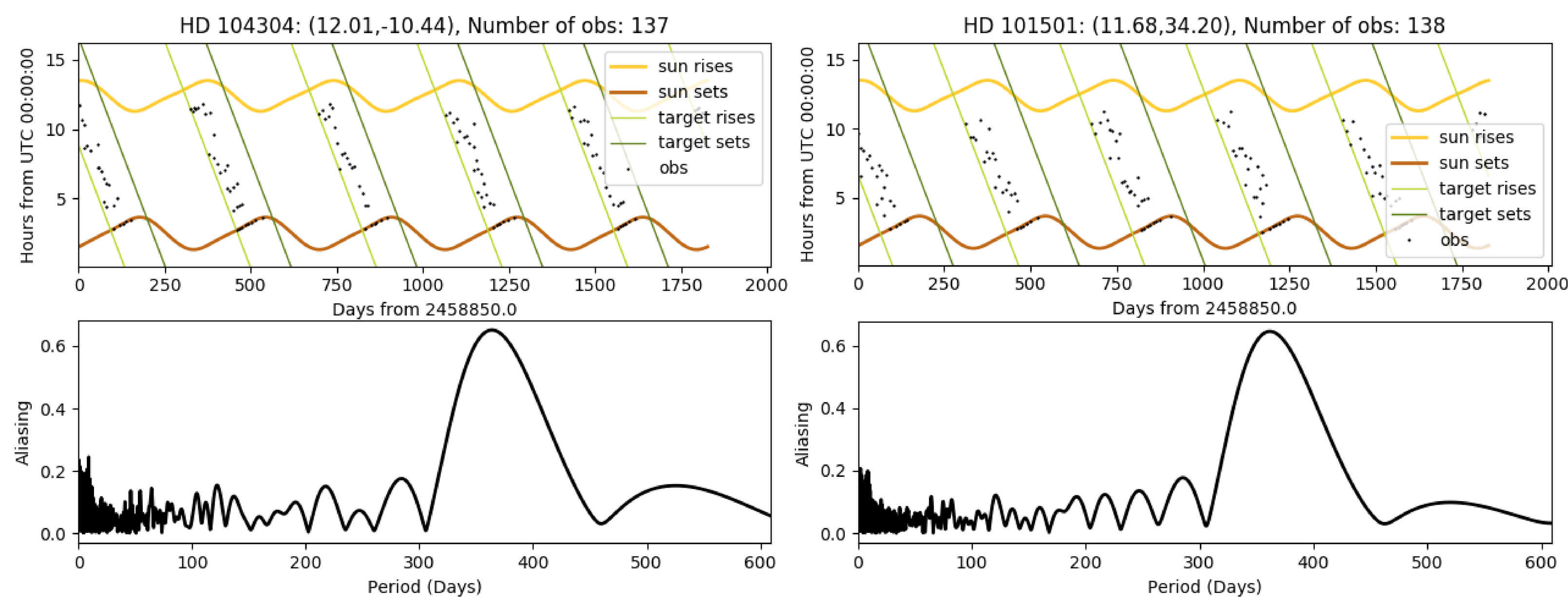


Figure: Stars near the median number of observations in the 3 cm/s 42 star survey. HD 104304 (left) has a shorter exposure time, but poorer position compared with HD 101501 (right).

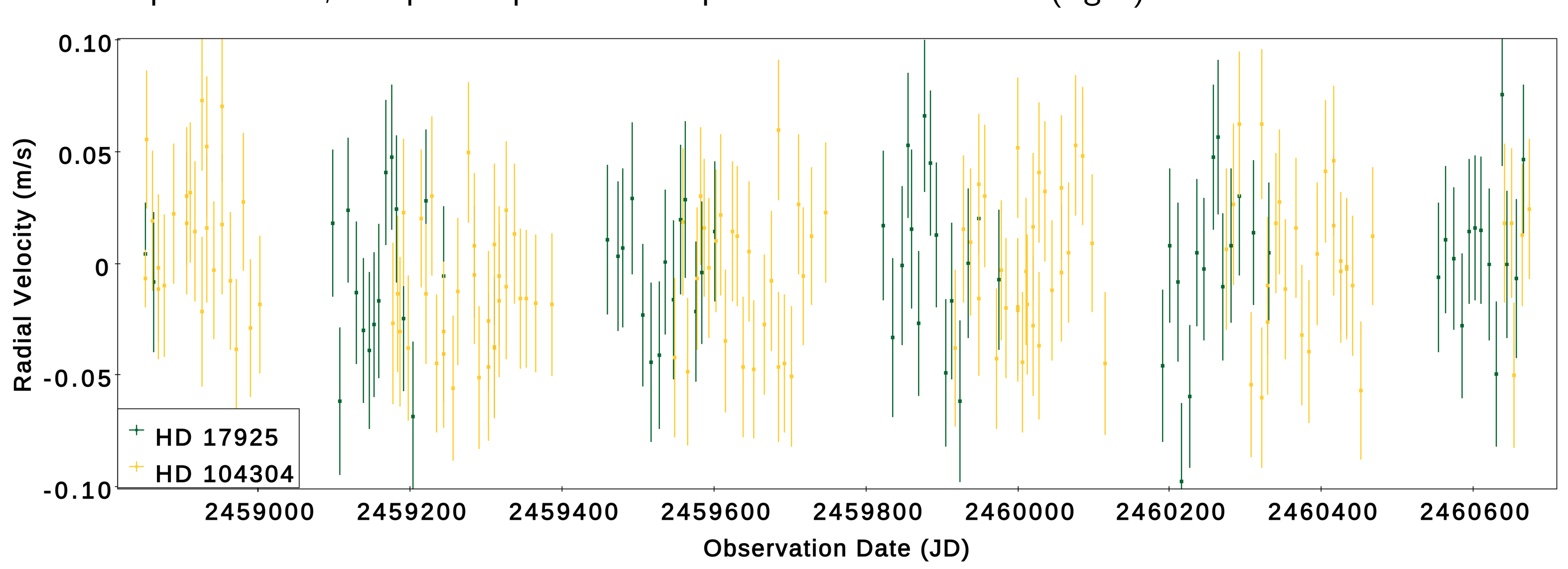
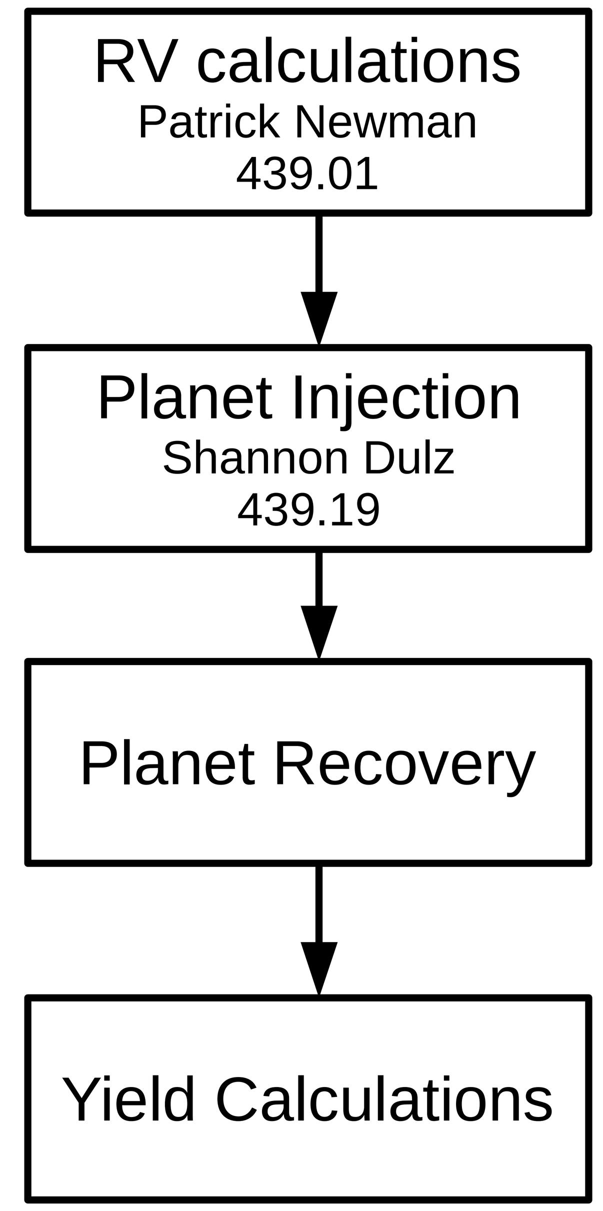


Figure: Sample RV timeseries of HD 104304, and HD 17925 with 1 σ error bars, assuming no planets. The RV measurements are generated by treating the precisions as the standard deviation of a gaussian, and randomly sampling.

Conclusions, overall plan, and future work



Both hour angle and last observation time provide useable observations distributions, with caveats. Pure hour angle weighting can cause "RA shadowing," with some stars recieving few to no observations. This is a greater problem with larger target lists and longer exposure times. Last observation time avoids these, but still shows significant variance in observation frequency. A combination of the two provides the best results, with about a factor of 2 difference between the most and least observed stars in smaller surveys with similiar observation times. Additional tweaks (eg: MINERVA's 3 observations in a night, our attempts at altitude weighting) had limited effect, and can in some cases be actively harmful. this is especially true for the very long integration times needed for high precision measurement.

Simulated radial velocities are roughly consistent with actual photon noise, though some detector parameters are poorly documented as to be nearly free. Careful coordination with instrument designers is necessary to ensure accuracy.

Precision even with perfect instrumentation and quiescent stars is limited, and a 1 cm/s "dream machine" will most likely require a very broad wavelength range (3 spectragraph arms), an 8 meter class telescope, or both.

All of this is only the first stage. With accurate radial velocity time series (modulo stellar activity), we can next inject signals from planets using existing demographic estimates. (See Shannon Dulz, poster 439.19 for details). Those signals will be fit, and we will determine both the extent to which planets are found, and how many of them are viable targets for the upcoming direct imaging missions.

Acknowledgements

This research is supported by a contract from the NASA Jet Propulsion Laboratory and Exoplanet Exploration Program in support of the HabEx Mission Study Science and Technology Definitions Team.

References

Swift et al. (2015). Miniature Exoplanet Radial Velocity Array (MINERVA) I. Design, Commissioning, and First Science Results. J. Astron. Telesc. Instrum. Syst. 1(2), 027002. dx.doi.org/10.1117/1.JATIS.1.2.027002

Plavchan et al. (2015) Radial Velocity Prospects Current and Future: A White Paper Report prepared by the Study Analysis Group 8 for the Exoplanet Program Analysis Group (ExoPAG). eprint arXiv:1503.01770

Howard, Andrew W. & Fultun, Benjamin J. (2016) Limits on Planetary Companions from Doppler Surveys of Nearby Stars. Publications of the Astronomical Society of the Pacific, 128(969), 114401. dx.doi.org/10.1088/1538-3873/128/969/114401

Beatty, Thomas G. & Gaudi, B. Scott. (2015) Astrophysical Sources of Statistical Uncertainty in Precision Radial Velocities and Their Approximations. Publications of the Astronomical Society of Pacific, 127(958), 1240. dx.doi.org/10.1086/684264