Voyage 2050 White Paper

Title: EarthFinder

Type of Activity: Space Based Project

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Description:

> *The primary science goals of EarthFinder are the precise radial velocity (PRV) detection, precise mass measurement, and orbit characterization of Earth-mass planets in Habitable Zone orbits around the nearest FGKM stars.*

EarthFinder is a NASA Astrophysics Probe mission concept selected for study as input to the 2020 Astrophysics Decadal. The study report and references are available here: https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Earth_Finder_Study_Rpt.pdf . We were selected to "establish the science case for going to space with a precise radial velocity mission." Consequently, we evaluate the scientific rationale for PRV measurements in space:

- **What can be gained from going to space?** *Evaluate the unique advantages that a space-based platform provides to enable the identification and mitigation of stellar activity for multi-planet signal recovery in PRV time series.*
- **What can't be done from the ground?** *Identify the PRV limit, if any, introduced from micro- and macro-telluric absorption in the Earth's atmosphere.*

The EarthFinder concept is based on a dramatic shift in our understanding of how PRV measurements could be made. We propose a new paradigm which brings the high precision, high cadence domain of transit photometry as demonstrated by Kepler and TESS to the challenges of PRV measurements at the cm/s level. This new paradigm takes advantage of: 1) broad wavelength coverage from the UV to NIR which is only possible from space to minimize the effects of stellar activity; 2) extremely compact, highly stable, highly efficient spectrometers (R>150,000) which require the diffraction-limited imaging possible only from space over a broad wavelength range; 3) the revolution in laser-based wavelength standards to ensure cm/s precision over many years; 4) a high cadence observing program which minimizes sampling-induced period aliases; 5) exploiting the absolute flux stability from space for continuum normalization for unprecedented line-by-line analysis not possible from the ground; and 6) focusing on the bright stars which will be the targets of future imaging missions so that EarthFinder can use a 1.45 m telescope.

A PRV semi-amplitude accuracy of 1 cm/s (10% mass uncertainty for 1 Earth-mass signal of 9 cm/s) on time-scales of several years can be achieved with ~5 cm/s individual measurement precision and taking advantage of binning down the uncertainties from hundreds of measurements. EarthFinder is based upon the heritage of Kepler spacecraft by Ball Aerospace, with a 1.45-m primary (diffraction limited to ~400 nm). The diffraction-limited beams of starlight are coupled into single-mode fibers illuminating three high-resolution, compact and diffraction- limited spectrometer “arms”, one covering the near-UV (280-380 nm), visible (VIS; 380-950 nm) and near-infrared (NIR; 950-2500 nm) respectively with a spectral resolution of greater than 150,000 in the visible and NIR arms. The observatory is optimized for the bright (V~5-6 mag) nearby main sequence stars. EarthFinder will be launched into an Earth-trailing (similar to Kepler and Spitzer) or Earth-Sun Lagrange-point orbit. It will have an instantaneous field of regard (FOR) of 70.7% of the celestial sphere, with a continuous viewing zone covering 29% of the sky greater than 45° out of the Ecliptic plane, with 3-6 months of visibility twice per year for targets within 45° of the Ecliptic plane.

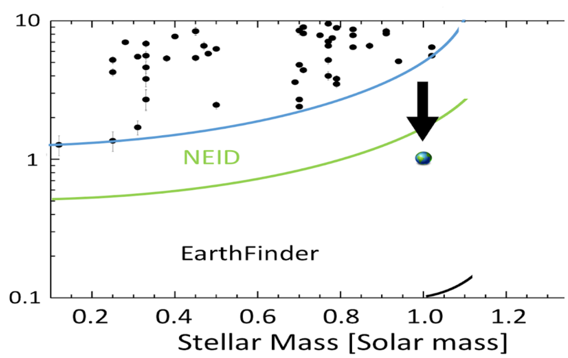

Figure 1: PRV-discovered exoplanets less than 10 M_{Earth} as a function of stellar mass and planet mass modulo the unknown inclination. Black circles are data from the NASA Exoplanet Archive. The blue-green orb corresponds to the Earth. The blue curve corresponds to the approximate current detection limit of the PRV method, the green curve corresponds to the NEID spectrometer (or similarly EXPRES or ESPRESSO), and the black curve corresponds to EarthFinder and its unprecedented 1 cms^{-1} sensitivity.

Study Findings:

> *“Measurements from space might be a final option if the telluric contamination problem cannot be solved.” - National Academies Exoplanet Science Strategy report, 2018*

1. The Earth's atmosphere will limit precise radial velocity (PRV) measurements to ~10 cm/s at wavelengths longer than ~700 nm and greater than ~30 cm/s at >900 nm, making it challenging to mitigate the effects of stellar activity without a measurement of the color dependence due to stellar activity in the PRV time series. EarthFinder can greatly reduce the effects of stellar jitter through its great spectral grasp, from the UV to the near-IR.
2. Simultaneous visible minus NIR PRV measurements ("PRV color") perfectly subtracts off the planet signal(s), uniquely isolating the chromatic stellar activity signal from the planet signal(s) in the PRV time-series. EarthFinder's broad spectral grasp offers the highest SNR measurement of this chromatic activity because the lack of the Earth's atmosphere permits PRV measurements at sufficient precision at wavelengths greater than ~700 nm. This unique space advantage will permit disentangling exoplanet and stellar activity signals.
3. "Line-by-line" analysis with high SNR and high-resolution data (R>100,000) can mitigate stellar jitter. In several cases from the ground, this technique has resulted in a reduction in stellar activity PRV RMS of 33-50% (Dumusque 2018, Lanza et al. 2018, Wise et al. 2018) but greater mitigation (>75%) is needed to detect Earth-mass analogs (Hall et al. 2018). Cegla et al. (2019) demonstrate that with better continuum normalization enabled by a space platform, the ability to distinguish between PRVs and stellar activity from convection and granulation strengthens dramatically.
4. The UV channel of our space platform permits the simultaneous observations in the near-UV of the Magnesium II lines at 280 nm in addition to the Calcium II H&K absorption lines, the latter of which routinely observed from the ground for PRV activity correlation analysis. These Mg II and Ca II activity sensitive spectroscopic features are produced at different scale heights in the chromosphere of Sun-like stars.
5. Diurnal and seasonal limitations of the ground introduce aliasing which draws power away from the planet signal frequencies and puts them into frequencies that are aliases of one day and one year. EarthFinder provides a large field of regard (FOR) and, for stars outside the continuous viewing zone, two long visibility windows per year which completely eliminates the diurnal alias and greatly reduces the annual alias. Multiple longitudinally-spaced ground-based telescopes and PRV spectrometers will only partially mitigate daily aliases due to airmass optimization, weather losses and zero-point velocity offsets between them.
6. EarthFinder's near continuous observing capability and the efficiency of its diffraction-limited spectrographs give EarthFinder's 1.45 m telescope an effective light gathering power of a much larger ground-based facility (~5 m equivalent in photons/sec).
7. EarthFinder is perfectly suited to find and characterize the masses and orbits of the planets orbiting ~50 bright main sequence stars (3<V<10 mag) which will be the targets for future NASA flagship missions to image and obtain spectra of nearby Earth-analogs.
8. High resolving power spectrographs (R~150,000) with simultaneous UV, visible and NIR coverage offers exciting new capabilities for general astrophysics, including direct exoplanet spectroscopy for characterization, stellar dynamos and asteroseismology, fundamental

atomic transitions in the Sun and other stars, following the water in the local Universe obscured by telluric water, and brown dwarf atmospheres.

9. A preliminary TRL and cost estimate for EarthFinder establishes this mission concept as a Probe ($1B) mission with a Kepler-sized telescope using a Kepler-derived spacecraft.

Study Recommendations:

1. Aligned with the top-level ESS recommendation, we recommend the immediate development of a testbed (e.g. upgrade-able) spectrographs (diffraction-limited and seeing-limited) facility with a target single measurement precision and long-term stability of 3 cm/s velocities to investigate the mitigation of stellar and/or solar activity and instrumentation development, to be directly followed by a space PRV mission. It is time now to commence the development of the next generation of PRV spectrometers, testing them on the ground first but also with an application for space. We envision a testbed analogous to NASA JPL's high-contrast imaging testbed facility which combines detailed analysis of error budgets with steady improvements in performance. The facility would require the necessary personnel and science, engineering and technical staff to support its development. This testbed could initially support disk-integrated Solar observations akin to the HARPS Solar telescope feed, so as to correlate and refine the analysis of the high-resolution spectroscopic data with the wealth of information available from heliophysics space and ground assets. This work will be placed into context of the vast wealth of information currently being obtained from visible wavelength seeing-limited spectrometers that are now operating with instrument stability of 10-30 cm/s (e.g. ESPRESSO, EXPRES, NEID). Experimental work must be carried out so that each entry in a detailed PRV error budget can be determined with sufficient accuracy so that the overall PRV precision can be predicted.

2. NASA and NSF should convene a workshop to be held by PRV instrument designers, Laser Frequency Comb (LFC) experts, and space electronics engineers to lay out a roadmap for future innovation and technology maturation. NASA and NSF should invest in the development program recommended by these experts. Wavelength standards such as LFCs can reduce the requirement on absolute instrument stability by turning many sources of instrument instability into a common-mode error which can be reduced by reference to a dense, ultra-stable comb of spectral lines. There remains significant work to develop space qualified frequency standards such as laser frequency combs or etalons capable of providing 1 cm/s long term stability over 3-5 years. These frequency standards must provide a dense comb of lines in the visible (0.4-1.0 m) and NIR (1.0-2.5 m) with few GHz spacing. Specifically:

    a. Extend silica and possibly Si_3N_4 microcombs to create pulse-pumped micro-astrocombs capable of delivering octave spanning spectra at ~10 GHz repetition rates in the soliton regime. Requires soliton microcomb dispersion engineering to maintain coupling efficiency of pumping wave and allow broad comb formation.

    b. Demonstration of small form-factor pulse pumping source (e.g. microcomb pumped by pulsed semiconductor laser).

    c. Packaging: incorporate integrated waveguide structures with the microresonator.

d. Continued rubidium D2 line-locked FP etalon development through exploration of advanced material designs and improved thermal stability.

3. NASA and NSF should invest in a national data analysis center or coordinated funding activity to address the signal processing required to model and mitigate the effects of tellurics and stellar activity. This effort should comprehensively span the variety of current and future approaches being explored to mitigate stellar activity, including line-by-line analysis, RV color, time-dependent and physically motivated modeling, extreme spectral resolution, simultaneous photometry, etc. to build comprehensive and specialized processing tools and statistical analyses. The scale of the effort required most likely necessitates the specialization of different teams, as opposed to individual PI-led teams attempting to cover all aspects.
4. NASA should bridge the NASA Astrophysics division with the expertise in Doppler spectroscopy of the Sun from NASA Heliophysics. In addition to theory and modeling efforts, this includes experiments to extend single-Iron line Solar Doppler observations to space-based, balloon-based, and ground-based multi-wavelength spanning Doppler measurements, and in the NIR free of telluric contamination, with the goal of both understanding our Sun and building better models of stellar activity for mitigating the PRVs of nearby stars.

State of the Field

The astronomical community is on the cusp of fulfilling the NASA strategic goal to "search for planetary bodies and Earth-like planets in orbit around other stars." (U.S. National Space Policy, June 28, 2010). Without PRV data, a future flagship direct imaging mission (e.g. LUVOIR, HabEx) may fall short of the ultimate goal to determine whether exoplanets can support life. PRVs provide several critical contributions to the science yield and optimization of such a mission. First, the masses of these planets will be needed to constrain the atmospheric models. Second, the orbits of these planets will be needed to assess habitability. Third, the target selection optimization, observation timing, and required number of direct imaging revisits depend on whether or not we will know a priori which nearby stars host Earth-mass planets in HZ orbits.

EarthFinder eliminates telluric contamination

Spectral contamination due to the telluric lines of Earth's atmosphere poses a serious challenge to PRVs. It is a known bottleneck for achieving higher RV precision in the NIR (Bean et al. 2010). Moreover, it was recently realized that even the "micro-telluric" lines (flux depths <2% and mostly <1%) at visible wavelengths can contribute to RV error budget at 20-50 cms^{-1} (Cunha et al. 2014; Artigau et al. 2014). This is a large term in the PRV error budget which is eliminated in space. These shallow but prevalent lines are challenging to model due to time-variability and a lack of accurate lab measurements of water lines. It is currently unclear how much we can eliminate their impacts on PRVs beyond the 0.5 m/s precision level (Fischer et al. 2016).

We perform simulations with synthetic spectra to assess the RV precision limit set by the telluric contamination for ground-based instruments. When no corrections are applied, tellurics induce considerable amounts of errors from cm/s to more than km/s for different spectral regions. **Division or modeling effectively removes some of the RV errors induced by tellurics,**

but not completely. These results represent an idealized situation and thus a lower limit, since it hinges on the perfect knowledge of the spectral continuum and such perfect knowledge is unrealistic from the ground. Additionally, several additional PRV error terms are introduced by telluric contamination and are not included in our simulations.

> *Through our simulations, the optimistic floor of RV precision from the ground due to the telluric contamination is around 2 cm/s in the visible (<700 nm) and 30 cm/s in the red/NIR.*

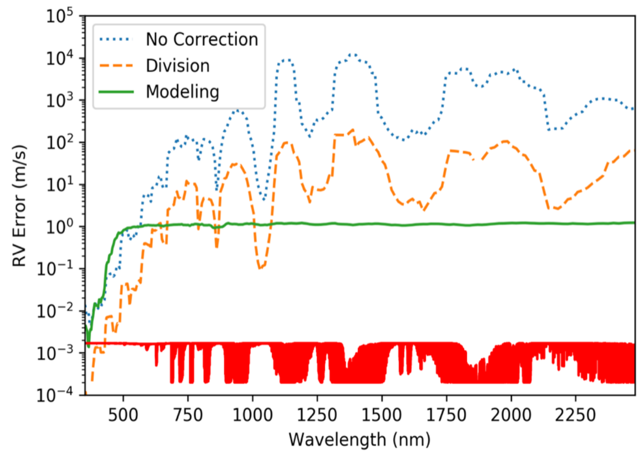

Figure 2: RV errors added by tellurics as a function of wavelength for 3 different methods. The RV error of each chunk is the RMS of RVs of this chunk over the simulated time span of 1 yr. The spectrum plotted in red at the bottom is telluric absorption.

EarthFinder can mitigate stellar jitter

EarthFinder will have the highest SNR measurements available from the near-UV to the NIR, with extremely high-res spectra, and with a near-perfect cadence sampling. Together, this will allow us to characterize stellar signals like never before with a variety of approaches including the RV color, line-by-line analysis, cadence, and simultaneous photometry, to mitigate the impact of stellar activity, therefore enabling the detection of Earth analogs. RV measurements are affected by different types of stellar signals at different timescales (Table 1). The most significant and difficult stellar activity signals to correct for are short-term activity and granulation, which need to be mitigated down to a few dozens of cm/s if we want to be able to characterize an Earth analog.

Space-based cadence:

EarthFinder's wide Field of Regard allows excellent sampling of the RV time series which is essential to avoiding aliases. The RV signal has a number of frequency components which may be periodic (planets) or quasi-periodic (stellar activity). From the ground, the sampling is limited by diurnal cycles, weather and sky visibility due to the time of year.

Radial Velocity Color:

Planet RV signals are achromatic: the same velocity reflex motion is measured at all wavelengths. Conversely, RV variations due to stellar activity are chromatic, particularly the most vexing effects from spots and faculae, since the flux emission from the stellar surface is temperature and thus wavelength dependent (Reiners et al. 2009, Tal-Or et al. 2018, Zechmeister et al. 2018). The signal in one wavelength regime (e.g. the blue or visible) will be a

Table 1: Known sources of stellar signals, that EarthFinder can model and mitigate, with their typical timescales and amplitudes for main sequence stars.

Stellar signal	Timescale	Amplitude	References
Oscillations	<15 min	~1 m/s	Kjeldsen et al. 95, Bouchy & Carrier 01, Butler et al. 04, Bedding & Kjeldsen 07
Flares	~1h (only active M)	<0.5 m/s	Saar 09, Reiners 09
Granulation	5 min- 2 days	~1 m/s	Del-Moro et al. 04, Del-Moro 04, Cegla et al. 13, Cegla et al. 14
Short-term activity (spots, faculae)	10-100 days (stellar rotation)	a few m/s	Saar & Donahue 97, Queloz et al. 01, Meunier et al. 10, Aigrain et al. 12, Dumusque et al. 14, Meunier et al. 17
Grav. redshift	10 days - 10 years	<0.1 m/s	Cegla et al. 12
Long-term activity	~10 years	1-20 m/s	Makarov 10, Dumusque et al. 11, Meunier et al. 13

summation of the planetary signals and the stellar activity, which will be different in a second wavelength regime (e.g. the red or NIR), a signal that is also a summation of the planetary signals and a modified stellar activity signal. Thus, by simultaneously measuring RVs in two different wavelength regimes and then subtracting these two time-series (e.g. the RV color time-series), the planet signals subtract out perfectly, leaving only the chromatic activity signal.

> *No other technique for mitigating stellar activity besides simultaneous measurements of RV color allows for the perfect isolation of the activity signal from the planet signals. EarthFinder, by virtue of spanning the largest spectral range, offers the highest SNR determination of RV color superseding any ground-based facility.*

Line-by-Line Analysis with High Spectral Resolution and Space-based Flux Continuum Normalization:

Spectral line by spectral line analysis is a critical technique to differentiate between activity signals and real planetary signals. Such analysis allows us to better understand how stellar activity perturbs stellar spectra and therefore RV measurements. In return, this will allow us to strongly mitigate the effect of stellar activity. Stellar activity modifies the shape and flux of spectral lines and therefore the highest resolution and precision is desirable to characterize this perturbing signal better. A preliminary study from Desort et al. (2007) shows that a resolution higher than R=100,000 allows us to measure a more significant signal for the bisector inverse slope (BIS), a proxy for the asymmetry variation of the cross-correlation function. Additionally, a study from Davis et al. (2017) has also shown that going to higher resolution is key in disentangling planetary from activity signals in RV measurements. Preliminary results show that a mitigation of stellar activity of nearly a factor of two is possible (Dumusque 2018) and there is optimism for much greater improvement, particularly from space. In agreement with Davis et al. (2017), Cegla et al. (2019) also argue that high spectral resolution is necessary if we are to use the line asymmetries as diagnostics of stellar noise from surface magneto-convection (i.e. granulation).

Recently, Cegla et al (2019) showed that several diagnostics derived from the stellar lines correlate strongly with the convection-induced RV shifts; thus, we may be able to use the stellar line profile variations as convection-noise mitigation tools. These authors created sun-as-a-star simulations based off a granulation parameterization derived from 3D magneto-hydrodynamic solar surface simulations. One of the strongest convection noise diagnostics came from measuring the variations in the stellar line profile depths/contrasts. The physical driver behind this is likely due to the fact that convective granules are formed higher in the photosphere and therefore have deeper line depths. Consequently, if more granules are present on the star at a given time we expect the disc-integrated profile to be both deeper and more blueshifted.

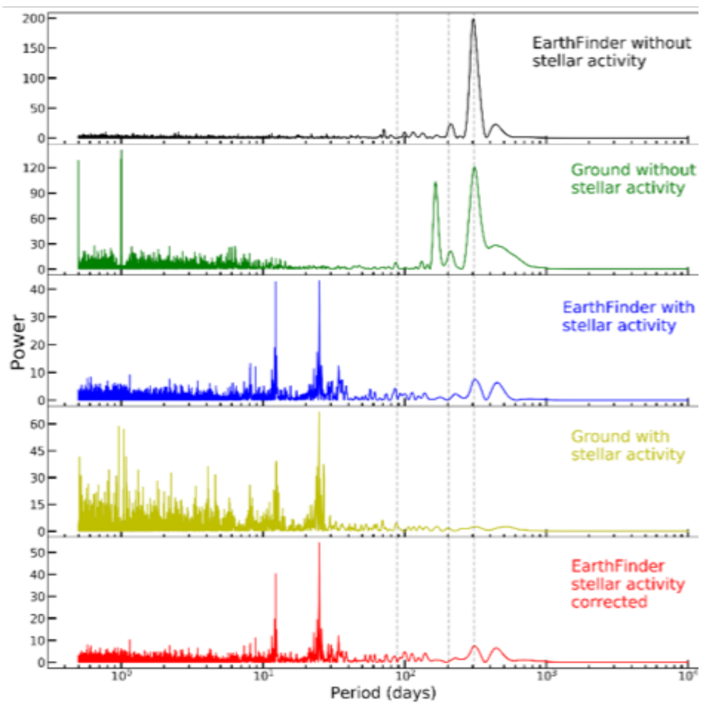

Figure 3: Bootstrap periodograms of simulated EarthFinder and ground-based RV time-series simulated, with a Mercury, Venus, and HZ super-Earth analog orbital periods indicated with the vertical dashed lines. The stellar activity correction shown reduces the rms due to activity by 61%.

The space-based spectra obtained with EarthFinder will not be affected by flux continuum normalization uncertainty which will provide spectral diagnostics that are less noisy, allowing us to much better mitigate stellar signals. In addition, space-based spectroscopy will also allow us to perform spectrophotometry, therefore giving another very important diagnostic for correcting stellar signals.

In line with this, the absolute line depths would only be available from a spectrometer in space, as ground-based data must be continuum normalized to remove contamination from Earth's variable atmosphere. The simulations in Cegla et al. (2019) show a strong correlation between the stellar line depth and the convection-induced RV shifts. Moreover, we also see that continuum normalizing the stellar lines does indeed increase the scatter in this correlation; in fact, this degradation in the correlation is sufficient to completely negate this diagnostic's noise mitigation ability (Cegla et al. 2019). The total variations in both line depth and RV will be greater if the magnetic field is lower, e.g. if it were closer to the quiet Sun. Nonetheless, the requirement to continuum normalize means the line depth will be a less powerful noise diagnostic from the ground and may not allow for the correction of any of the convection induced variations without going to space.

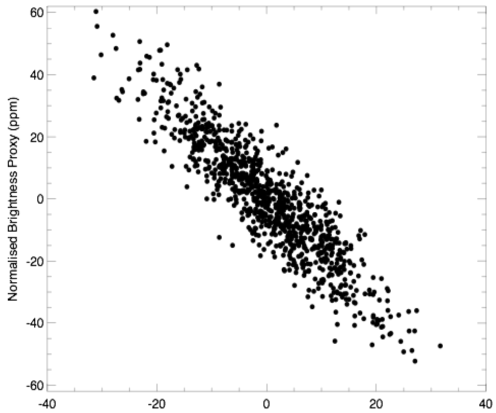

Figure 4: Integrated line flux vs RV (Cegla et al. 2019).

For example, Cegla et al. (2019) has shown the convective-induced brightness measurements, as derived from integrating the area under their simulated line profile, are even more strongly correlated with the convective-induced RV shifts and may allow us to remove >50% of the RV variability. Moreover, convective-induced brightness variations would require precision measurements of 10s of parts per million (ppm), which is only achievable from space. A space-based spectrometer would naturally provide simultaneous RV and brightness proxy measurements.

Science Traceability Matrix

Table 2: The Science Traceability Matrix is used to derive the EarthFinder functional requirements.

Goals	Science Objectives	Scientific Measurement Requirements		Instrument Functional Requirements	Projected Performance	Mission Functional Requirements (Top Level)
		Physical Parameters	**Observables**			
Goal 1: Seek out new worlds and determine if they might be habitable	O1: Determine if small (0.8-1.7 R_E) planets exist around nearby Sun-like stars and continuously orbit within the HZ; Survey a sample of FGK stars to reach HZ completeness > 75% for exo-Earths ($m\sin i$ = 0.5 – 4.3 M_E at i = 60 deg).	Periodic changes and trends in the radial (line-of-sight) velocity of the star to determine semi-major axes, eccentricities, and minimum masses of planets to 10% for 1 Earth-mass planets at i = 90 deg. Use orbital elements and properties of the star to infer the effective temperature and potential for habitability of the planets.	Stellar Spectrum: Measure line centroids relative to a local wavelength standard with noise equivalent of < 10 cm/s (per epoch) Stellar Activity: (a) Spectral lines shapes over a broad wavelength span (b) Equivalent widths of activity indicator lines to 1% (c) Spectrophotometry to < 1% at low resolving power R=100	Spectral range: 0.4-2.4 µm with median resolving power R > 140,000 Instrument Doppler noise equivalent < 10 cm/s (in 1 hr) and 1 cm/s (over mission duration) UV spectral range: 0.24-0.4 um with resolving power R > 1000 Photometer	Two stabilized Echelle spectrometers cover 0.4-2.5 µm range simultaneously with R = 150,000 Spectrograph Doppler noise ~5 cm/s/hr$^{1/2}$ UV grating spectrometer with R=3000 0.5 % relative spectrophotometry	Observe 60 stars >80 times a year Time baseline > 4 yr Telescope aperture > 1.2 m, diffraction limited at 0.4 µm. Pointing = 10 mas (1-σ 2 axis jitter) Spacecraft velocity < 1 cm/s FOR = 71% of celestial sphere
	O2: Survey a nearby sample of sunlike stars and cool dwarfs (1.1 $M_S \le M \le 0.1 M_S$) and determine the architecture of their planetary systems out to beyond snow-line orbits $P_{ORB} \le 5$ yr.		Stellar Spectrum: Measure line centroids relative to a local wavelength standard with noise equivalent of <10 cm/s (per epoch) Stellar Activity: (see above)	Same as above		Survey time > 4 yr

Cost Assessment

Figure 5 (right): A generic error budget for a high-resolution RV spectrometer has many terms which the EarthFinder eliminates or mitigates through operation in space (red), use of a diffraction limited spectrometer (orange), and a single-mode fiber (yellow), or via calibration with a LFC (green).

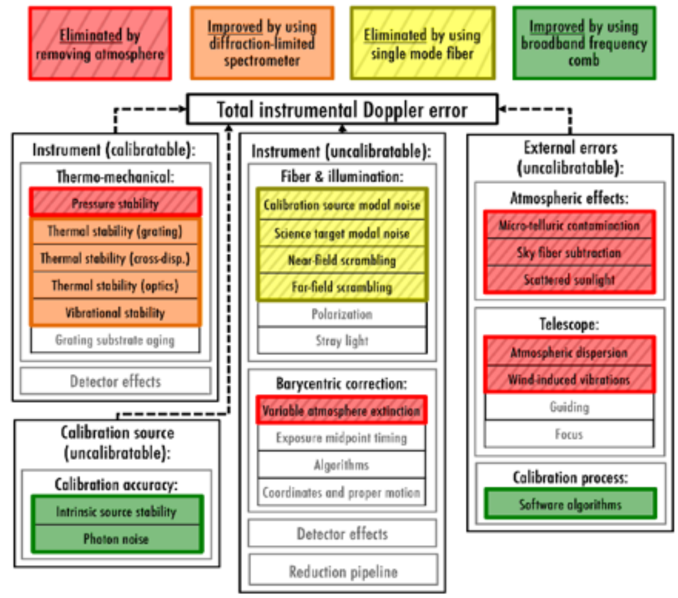

Table 3: Cost Estimate

Work Breakdown Structure (WBS) Elements	Team X Estimate
1.0, 2.0, & 3.0 Management, Systems Engineering, and Mission Assurance	$60 M
4.0 Science	$15 M
5.0 Payload System	$265M
5.01 Payload Mgmt.	-
5.02 Payload SE	-
5.03 Payload S&MA	$5 M
5.04 OTA	$45 M
5.05 Instrument	$195 M
5.01 Inst. Mgmt.	$10 M
5.02 Inst. SE	$15 M
5.03 Inst. S&MA	$5 M
5.04 Sensor	$150 M
5.03 60K Cryocooler	$10 M
5.10 Instrument I&T	$20 M
6.0 Flight System	$185 M
7.0 & 9.0 Mission Op Preparation & Ground Data Systems	$30 M
10.0 ATLO	$25 M
11.0 Education and Public Outreach	-
12.0 Mission and Navigation Design	$5 M
Reserves (30%)	$175 M
8.0 Launch Vehicle (LV)	$150.00 M
Total Cost (including LV)	**$905 M**

Disclaimer: The costs presented in this report are ROM estimates; It is possible that each estimate could range from as much as 20% percent higher to 10% lower. The costs presented are based on Pre-Phase A design information, which is subject to change. The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

No high-fidelity instrument or mission design studies were funded. However, JPL was able to carry out a TeamX study to establish whether EarthFinder was consistent with the anticipated cost of a Probe Class mission. The TeamX cost estimate is $755M ($905M including launch vehicle in FY18 dollars). The estimate includes 30% of unreserved costs as cost reserves as required by JPL best practices. The TeamX estimate is based on a detailed estimate of the (WBS 5) payload system costs, and rule of thumb percentages for the other WBS elements of the mission. The TeamX detailed payload system estimate is based the NASA Instrument Cost Model (NICM) version VIII for the Instrument (Fine Guidance Camera, all three spectrometer arms, the beam splitter, and the laser comb); a multivariable parametric cost model by Stahl & Henrichs (2016) for the Optical Telescope Assembly (OTA); and the NICM VIII cryocooler cost model for the 60K Cryocooler.

References from NASA-submitted probe study report:

Aigrain, S., Pont, F. and Zucker, S. 2012, MNRAS 419, 3147
Alexander, D.R., et al. 1989, ApJ, 345, 1014
Allard, F., 2014, Exploring the Formation and Evolution of Planetary Systems, Proceedings of the International Astronomical Union, IAU Symposium, Vol. 299, 271
Artigau, ́E. et al., 2014, SPIE, 9147, 15
Auman, J. Jr. 1967, ApJS, 14, 171
Baraffe, I., et al. 2015, A&A, 577, 42
Bao, C., Zhang, L., Matsko, A., Yan, Y., Zhao, Z., Xie, G., Agarwal, A.M., 2014, Optics Letters 39, 6126
Baranne, A., et al. 1996, A&AS, 119, 373
Bean, J. Seifhart, A., Hartman, H., et al. 2010, ApJ, 713, 410
Beatty, T., & Gaudi, B.S, 2015, PASP, 127, 1240
Bedding, T. R., Kjeldsen, H. 2007, Comm. In Asteroseismology 150, 106
Beha, K., Cole, D. C., Del'Haye, P., Coillet, A., Diddams, S. A., Papp, S. B., 2015, https://arxiv.org/abs/1507.06344
Bertaux, J., et al., "TAPAS, a web-based service of atmospheric transmission computation for astronomy." In 13th International HITRAN Conference. 2014.
Boisse, I., Bouchy, F., Hébrard, G. et al. 2011, A&A 528, 4
Bouchy, F., Carrier, F. 2001, A&A 374, 5
Bourrier, V., et al. 2017, AJ, 154, 121
Bourrier, V., et al. 2016, A&A, 591, 121
Bourrier, V., et al. 2014, A&A, 565, 105
Brasch, V., Geiselmann, M., Herr, T., Lihachev, G., Pfeiffer, M. H. P., Gorodetsky, M. L. and Kippenberg, T. J., 2016, Science 351, 3570
Broomhall, A.M., et al. 2009, A&A 503, 241
Butler, R. P., et al., 1996, PASP, 108, 500
Butler, R. P., Bedding, T. R., Kjeldsen, H. et al. 2004, ApJL 600, 75
Carlson, D. R. et al. 2017, arXiv:1711.08429
Cauley, P. W., et al. 2018, AJ, 156, 189
Cavallini, F., Ceppatelli, G. R. A. 1985, A&A 143, 116
Cegla, H. M., et al., 2019, submitted
Cegla, H. M., Watson, C. A., Marsh T. R. et al. 2012, MNRAS 421, 54
Cegla, H. M.; Shelyag, S.; Watson, C. A., Mathioudakis, M. 2013, ApJ, 763, 95
Cegla, H. M. and Stassun, K. G., Watson, C. A. et al. 2014, ApJ 780, 104
Chaplin, W., et al., 2019, submitted, arXiv 1903.00657
Charbonneau, D., et al., National Academies of Sciences, Engineering, and Medicine, Exoplanet Science Strategy. Washington, DC: The National Academies Press. https://doi.org/10.17226/25187 (2018)
Chen, J. & Kipping, D., 2017, ApJ, 834, 17
Crepp, J. R. et al., 2016, Proc. SPIE 9908, 990819
Cunha, D., Santos, N. C., Figueira, P., et al. 2014, A&A, 568, A35
Damasso, M., Bonomo, A.S., Astudillo-Defru, N. et al. 2018, A&A 615, 69
Davis, A. B., Cisewski, J., Dumusque, X. et al. 2017, ApJ 846, 59
Delisle, J.-B., Ségransan, D., Dumusque, X. et al. 2018, A&A 614, 133
Del Moro, D. 2004, A&A 428, 1007
Del Moro, D., Berrilli, F., Duvall, Jr., T. L. et al. 2004, Solar Physics 221, 23
Desort, M., Lagrange, A.-M., Galland, F. et al. 2007, A&A 473, 983
Diaz, R. F., Rey, J., Demangeon, O. et al. 2016, A&A 591, 146
Diddams, S., 2010, J. Opt. Soc. Am. B 27, B51-B62
Dravins, D., Lindegren, L., & Nordlund, A., 1981, A&A 96, 345
Dulz, S., Plavchan, P., et al., 2019, in prep.
Dumusque, X., Udry, S., Lovis, C. et al. 2011a, A&A 525, 140
Dumusque, X., Santos, N. C., Udry, S. et al. 2011b, A&A 527, 82
Dumusque, X., Lovis, C., Segransan, D. et al. 2011c, A&A 535, 55

Dumusque, X., Boisse, I., Santos, N. C. 2014, ApJ 796, 132
Dumusque, X., Borsa, F., Damasso, M. et al. 2017, A&A 598, 133
Dumusque, X. 2018, A&A 620, 47
Ehrenreich, D. & Desert, J.-M. 2011, A&A 529, 136
Ehrenreich, D., et al. 2015, Nature, 522, 459
Elsworth, Y., Howe, R. Isaak, G. R. et al. 1994, MNRAS 269, 529
Finsterle, W., Jefferies, S.M. Cacciani, A. et al., 2004, Solar Physics, 220, 317
Fischer, D. A., Anglada-Escude, G., Arriagada, P., et al. 2016, PASP, 128, 066001
Fulton, B.J., et al., 2018., PASP, 130, 044504
Gagné, J., et al., 2017, ApJ, 841, L1
Gaudi, B.S., et al., HabEx Interim Report
Grunblatt, S. K., Howard, A. W., & Haywood, R. D. 2015, ApJ 808, 127
Gullikson, K., Dodson-Robinson, S., & Kraus, A., 2014, AJ, 148, 53
Hall, R. D., Thompson, S. J., Handley, W. et al. 2018, MNRAS 479, 2968
Halverson, S. et al. 2014, PASP, 126, 445
Haswell, C.A., et al., 2012, ApJ 760, 79
Halverson, S., Mahadevan, S., Ramsey, L., Terrien, R., Roy, A., Schwab, C., Bender, C., Hearty, F., Levi, E., Osterman, S., Ycas, G., & Diddams, S., 2014, Proc SPIE , 9147, 91477Z
Halverson, S., et al. 2016, SPIE, 9908, 6P
Haywood, R. et al. 2016, MNRAS, 457, 3637
Haywood, R. D., Collier Cameron, A, Queloz, D. et al. 2014, MNRAS 2014, 2517
Herr, T., Brasch, V., Jost, J. D.,Wang, C. Y., Kondratiev, N. M., Gorodetsky, M. L., Kippenberg, T. J., 2014, Nature Photonics , 8, 145
Herr, T., Gorodetsky, M. L., Kippenberg, T. J., 2015, arXiv:1508.04989
Herrero, E., et al., 2016, A&A, 586, A131
Hill, F. 2009, in Astronomical Society of the Pacific Conference Series, Vol. 416, Solar-Stellar Dynamos as Revealed by Helio- and Asteroseismology: GONG 2008/SOHO 21, ed. M. Dikpati, T. Arentoft, I. Gonzalez Hernandez, C. Lindsey, & F. Hill, 557
Huélamo, N., Figueira, P., Bonfils, X. et al. 2008, A&A 489, 9
Howe, R., Hill, F., Komm, R., et al. 2011, in Journal of Physics Conference Series, Vol. 271, Journal of Physics Conference Series, 012058
Jones, D. E., Stenning, D. C., Ford, E. B. et al. 2017, arXiv 171101318J
Joshi, C. et al. 2016, Opt. Lett. 41, 2565
Jovanovic, N., et al., 2018, A&A, 604, 122
Kipping, D., 2013, MNRAS, 434, L51
Kjeldsen, H., Bedding, T. R. 1995, A&A 293, 87
Kurucz, R. L. 2005, Memorie della Societa Astronomica Italiana Supplementi, 8, 14
Lagrange, A.-M., Desort, M., Meunier, N. 2010, A&A 512, 38
Lamb, E. S., Carlson, D. R., Hickstein, D. D., Stone, J.R., Scott A. Diddams, S. A., Papp, S. B., 2018, Phys. Rev. Applied 9, 024030
Lee, S.H., Oh, D.Y., Yang, Q., Shen, B., Wang, H., Yank, K.Y., Lai, Y.H., Yi, X., Li, X., Vahala, K., "Towards visible soliton microcomb generation", Nature Communications, Volume 8, No.1295 (2017).
Langhoff, S.R., Schwenke, D.W. & Patridge, H. 1996, Molecules in astrophysics: probes & processes: abstract book, IAU symposium 178: 1-5 July 1996, Leiden, The Netherlands. Edited by Ewine Fleur van Dishoeck, p. 295.
Lanza, A., et al., 2018, A&A 616, 155
Lecavelier des Etangs, A., et al., 2012, A&A, 543, 4
Lindegren, L., Dravins, D. 2003, A&A 401, 1185
Lissauer, J., et al., 2011, ApJ, 197, 8
Lovis, C., Dumusque, X., Santos, N. C., et al. 2011, arXiv 1107.5325
Makarov, V. V. 2010, ApJ, 715, 500
Marchwinski, R. C., Mahadevan, S., Robertson, P. et al. 2015, ApJ 798, 63

Meunier, N., Desort, M., Lagrange, A.-M. 2010, A&A 512, 39
Meunier, N., Lagrange, A.-M. 2013, A&A 551, 101
Meunier, N., Lagrange, A.-M., Borgniet, S. et al. 2015, A&A 583, 118
Meunier, N., Lagrange, A.-M., Borgniet, S. 2017, A&A 607, 6
Moille, G. Li, Q., Kim, S., Westly, D., and Srinivasan, K., 2018, Opt. Lett. 43, 2772
National Academies of Sciences, Engineering, and Medicine. 2018. Exoplanet Science Strategy. Washington, DC: The National Academies Press. https://doi.org/10.17226/25187
Newman, P., Plavchan, P., et al., in prep. Https://github.com/pdn4kd/dispatch_scheduler
Nürnberg, J., Alfieri1 C., Waldburger D., Golling M. and Keller, U., 2018, Advanced Photonics Congress (BGPP, IPR, NP, Networks, NOMA, Sensors, SOF, SPPCom), JW2I.4
Obrzud, E., Rainer, M., Harutyunyan, A., Chazelas, B., Cecconi, M., Ghedina, A., Molinari, E., Kundermann,S., Lecomte, S., Pepe, F., Wildi, F., Bouchy, F., Herr, T., 2018, arXiv:1808.00860
Owen, W.M. Jr & Jackson, A.P. 2012, MNRAS, 425, 2931
Pallé, P. L., Roca Cortes, T. Jimenez et al. 1999, ASPC 173, 297
Passegger, V.M., Wende-von Berg, S., &
Reiners, A. 2016, A&A 587, 19
Pinte, C., et al. 2018, A&A, 609 47
Plavchan, P., et al., "Radial Velocity Prospects
Current and Future," 2015a, ExoPAG Study Analysis Group white paper report, arXiv: 1503.01770
Queloz, D. and Henry, G. W. and Sivan, J. P. et al. 2001, A&A 379, 279
Queloz, D., Bouchy, F., Moutou, C. et al. 2009, A&A 506, 303
Rajpaul, V., Aigrain, S., Osborne et al. 2015, MNRAS 452, 2269
Rajpaul, V., Aigrain, S., Roberts, S., 2016, MNRAS 456, 6
Reiners, A., 2009, A&A, 498, 853
Reiners, A., Mrotzek, N., Lemke, U. et al. 2016, A&A 587, 65
Roudier, T., Svanda, M., Rieutord, M. et al. 2014, A&A 567, 138
Saar, S. H. and Donahue, R. A. 1997, ApJ 485, 319
Saar, S. H. 2009, Cool Stars 15 proceedings, American Institute of Physics Conference Series 1094, 152
Salabert, D., Turck-Chieze, S., Barriere, J. C., et al. 2009, in Astronomical Society of the Pacific Conference Series, Vol. 416, Solar-Stellar Dynamos as Revealed by Helio- and Asteroseismology: GONG 2008/SOHO 21, ed. M. Dikpati, T. Arentoft, I. Gonzalez Hernandez, C. Lindsey, & F. Hill, 341
Sameshima, H., et al., 2018, "Correction of Near-infrared High-resolution Spectra for Telluric Absorption at 0.90-1.35 μm." In Publications of the Astronomical Society of the Pacific, vol. 130
Schrijver, C.J. & Zwann, C., 2000, Cambridge Astrophys. Ser., Vol. 34
Schwab, C., Sturmer, A., Gurevich, D., Fuhrer, T., Lamoreaux, S.K., Walther, T., Quirrenback, A., 2015, "Stabilizing a Fabry–Perot Etalon Peak to 3 cms-1 for Spectrograph Calibration", PASP, 127, 880
Schwab, C., Feger, T., Sturmer, J., Seifhart, A., Gurevich, Y.V., Rogozin, D., et al. 2018, Proc. SPIE, 10702, 1070272
Seifahrt, A., Kaufl, H. U., Zangl, G., Bean, J. L., Sithajan, Sirinrat, Jian Ge, and Ji Wang, 2016, "Telluric Line Effect on High Precision Radial Velocity Survey of K and M Dwarfs." In American Astronomical Society Meeting Abstracts, vol. 227
Smette, A., et al., 2015, A&A, 576, A77
Spencer, D.T. et al, 2017, DOI: 10.1109/IPCon.2017.8116130

Stahl, H. P. & Henrichs, T. Proc SPIE, 2016, 9911, 99110
Suh, M.-G., Yi, X., Lai, Y.-H., Leifer, S., Grudinin, I. S., Vasisht, G., et al. 2018, Nature Photonics, in press. arXiv:1801.05174
Teague, R., et al., 2018, ApJ, 860 12
Thompson, A. P. G.,Watson, C. A., de Mooij, E. J.W. et al. 2017, MNRAS 468, 16
Title, A. M., Tarbell, T. D., Topka, K. P. et al., 1989, ApJ 336, 475
Tuomi, M., Anglada-Escudé, G. 2013a. A&A, 556, 111
Tuomi, M., Anglada-Escudé, G., Gerlach, E. et al., 2013b, A&A 549, 48
Ulmer-Moll, S., et al. 2019, A&A 621, 79
Vidal-Madjar, A., et al. 2003, Nature, 422, 143
Wang P.H., Jaramillo-Villegas J.A., Xuan Y., et al. 2016, Opt. Express 24, 1089.
Wang, S. X., et al. 2019, AJ, submitted
Wise, A. W., Dodson-Robinson, S. E., Bevenour, K. et al. 2018, AJ 156, 180
Wise, A.W., Plavchan, P., et al., 2019, in prep.
Wright, J. T., et al. 2013, ApJ, 770, 119
Wright, J.T., et al. 2004, ApJS, 152, 261
Yan, F. & Henning ,T. 2018, Nature Astronomy, 2, 714
Yi, X., Vahala, K., Li, J., Diddams, S., Ycas, G., Plavchan, P., Leifer, S., Sandhu, J., Vasisht, G., Chen, P., et al. 2016, Nature Comm. 7, 10436
Yi, X., Yang, Q.-F., Yang, K. Y., Suh, M.-G., & Vahala, K., 2015, Optica 2, 107
Zechmeister, M., Reiners, A., Amado, P. J. et al. 2018, A&A 609, 12