EarthFinder

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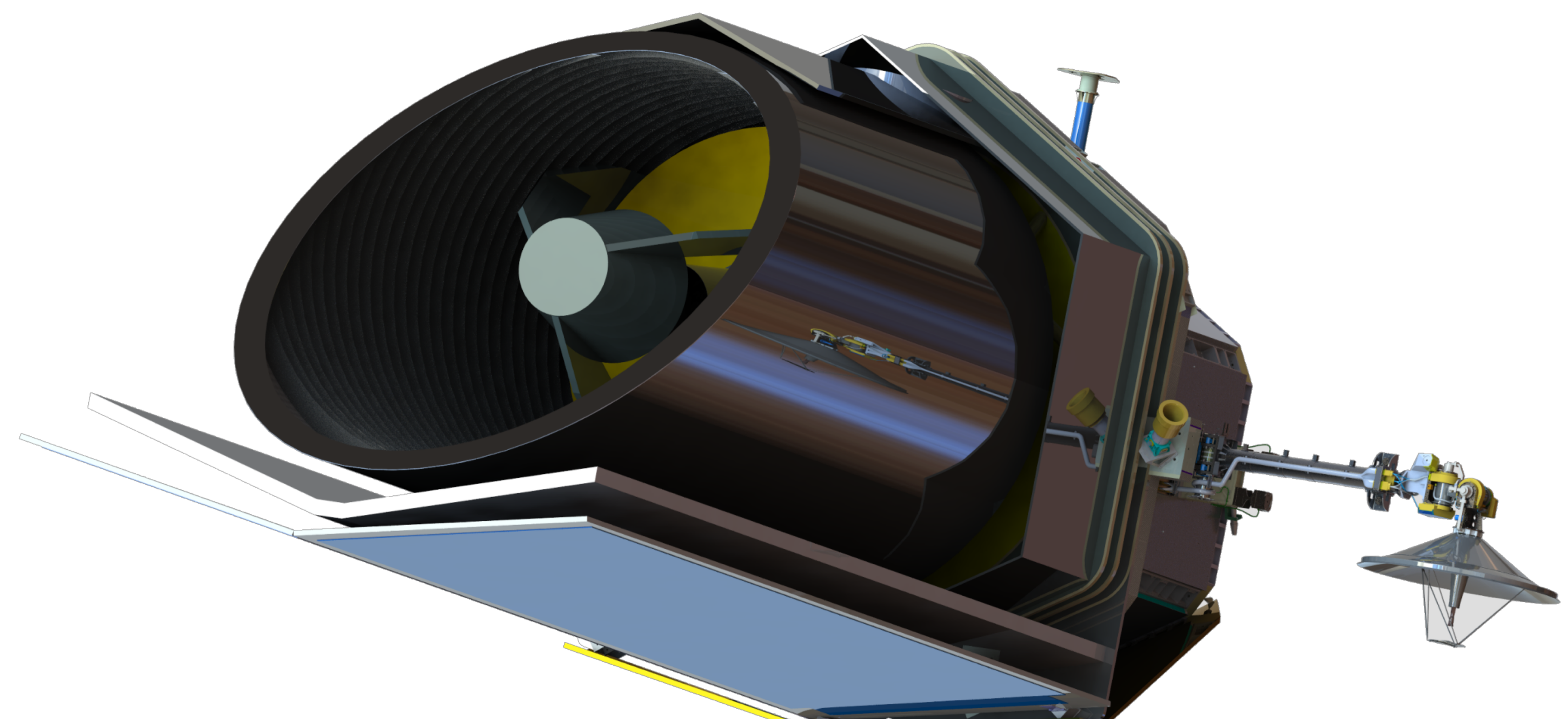
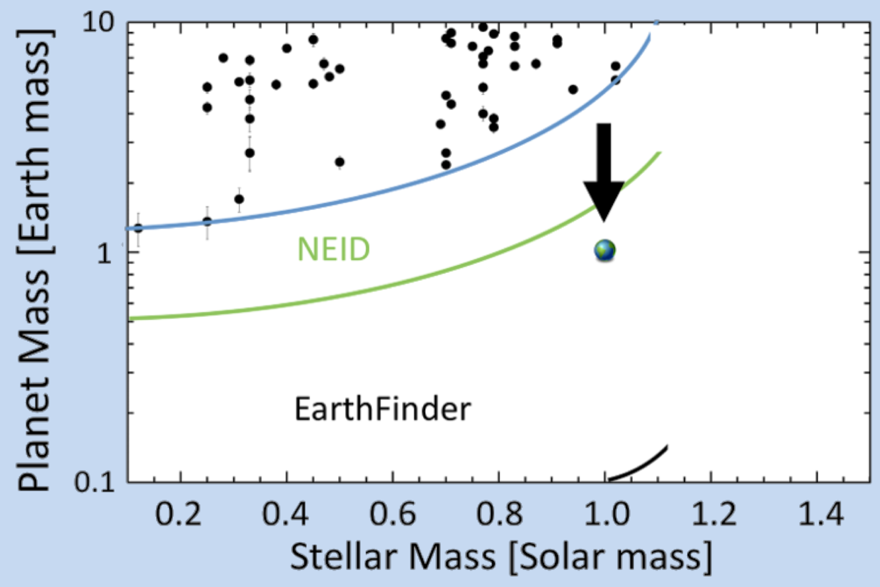


Spacecraft rendering from Ball Aerospace

Science

Primary Objectives

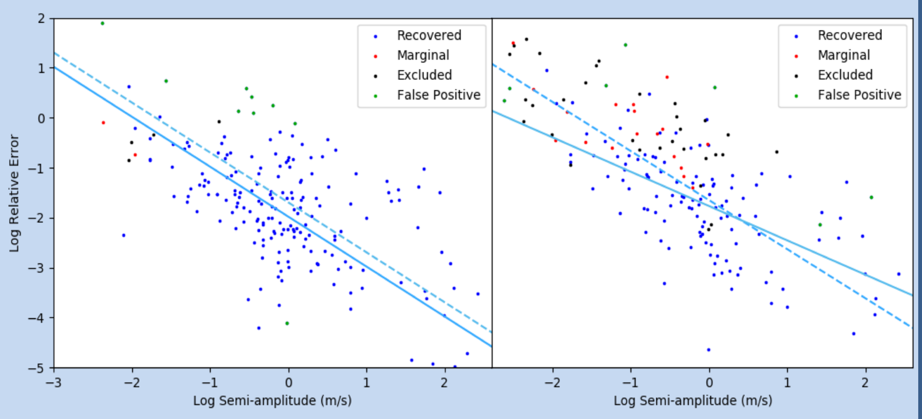
The primary science goals of EarthFinder are the radial velocity (RV) detection, mass measurement, and orbit characterization of Earth-mass planets in Habitable Zone (HZ) orbits around the nearest 25-50 FGKM stars. These goals correspond to a radial velocity semi-amplitude precision of 1 cm/s on time-scales of several years, given the 9 cm/s reflex motion velocity semi-amplitude of the Sun in response to Earth and a 10% mass determination precision.



Above: Black: RV-discovered exoplanets; blue-green orb: Earth; blue curve: approximate current detection limit; green curve: NEID spectrometer; black curve: EarthFinder.

Major Findings

- EarthFinder will be able to detect Earth-like planets around nearby Sun-like stars
- For an Earth-mass planet in the HZ (~ 9 cm/s), EarthFinder outperforms our ground-based survey by a factor of 3 in semi-amplitude accuracy
- Telluric contamination limits RV precision from the ground to ~2 cm/s in the visible and ~30 cm/s at >700 nm. If RV color is necessary to mitigate activity, it will not be possible from the ground
- Using a simple linear model for RV color, we can correct the RV RMS activity by 62%.
- EarthFinder eliminates the diurnal alias and reduces the annual alias, allowing us to distinguish between stellar and planetary signals at periods of 0.5-2 years
- EarthFinder offers superior continuum normalization for the best line-by-line analysis of stellar activity

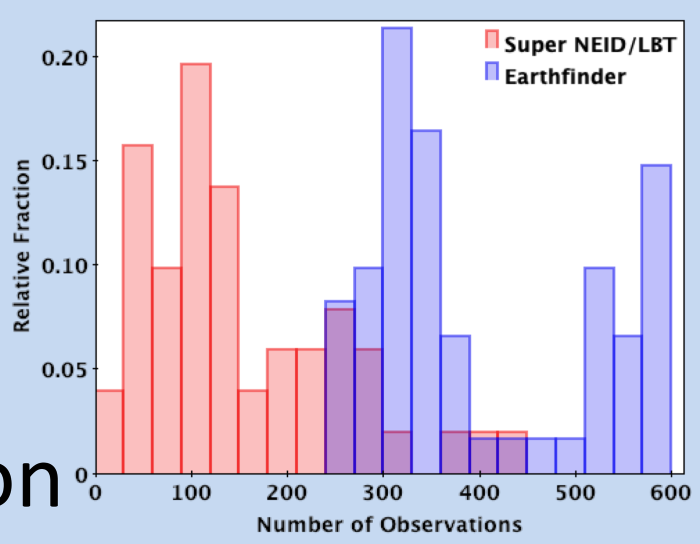


Above: Left: Log of the absolute relative error in the recovered vs. injected velocity semi-amplitude as a function of semi-amplitude for simulated planets in our EarthFinder survey. Right: The same, but for a similar ground-based survey. A linear fit is shown as a solid line. The dashed line is the fit line from the other panel for comparison.

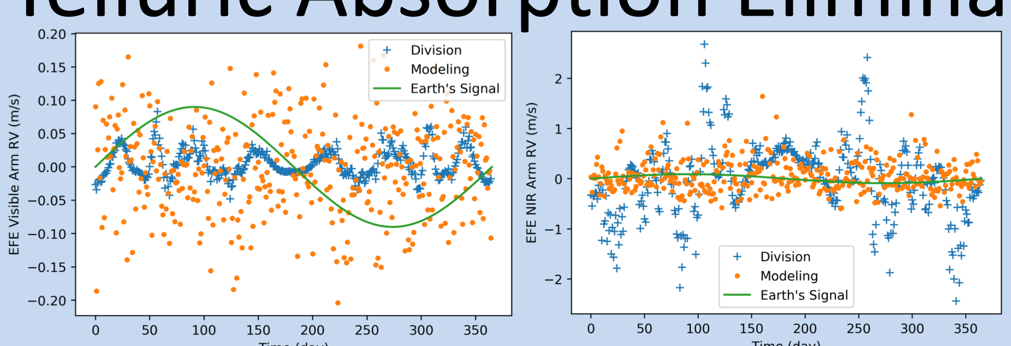
Cadence Advantages

- One-day cadence aliasing from ground-based observations draws significant power away from Earth-analog signals
- A large number of observations is necessary to unambiguously detect RV signals from an Earth-mass HZ planet
- EarthFinder is unrestricted by diurnal/seasonal cycles, has no declination or right ascension bias, and has large continuous viewing zones, which allow us to achieve optimal sampling

Right: Dedicated EarthFinder survey (blue) of 61 targets outperforms a 25%-time survey on a 8-m ground-based facility (red) of 53 targets in the number of observations per star.

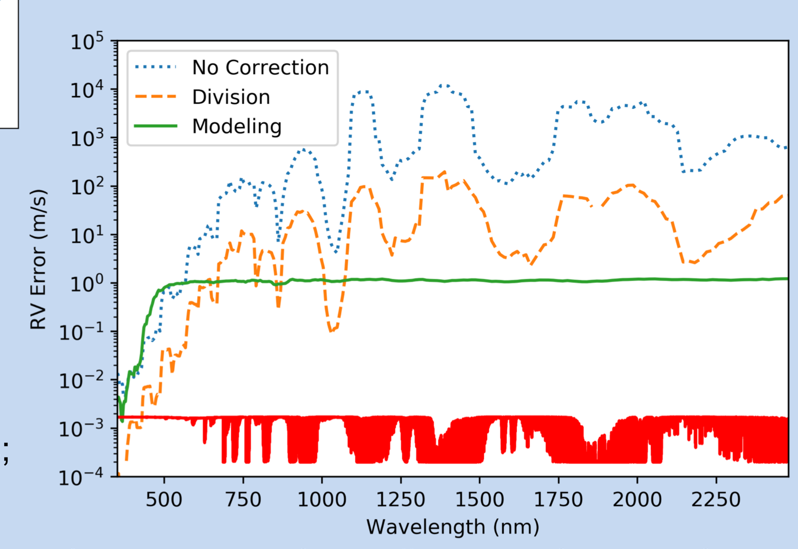


Telluric Absorption Elimination



Above: Left: Ground-based EarthFinder equivalent (EFE) spectrograph RV Signal vs. time in the visible, with two different telluric mitigation techniques. Assumes SNR = 100 per pixel for R = 120,000. Right: Same, but in the NIR.

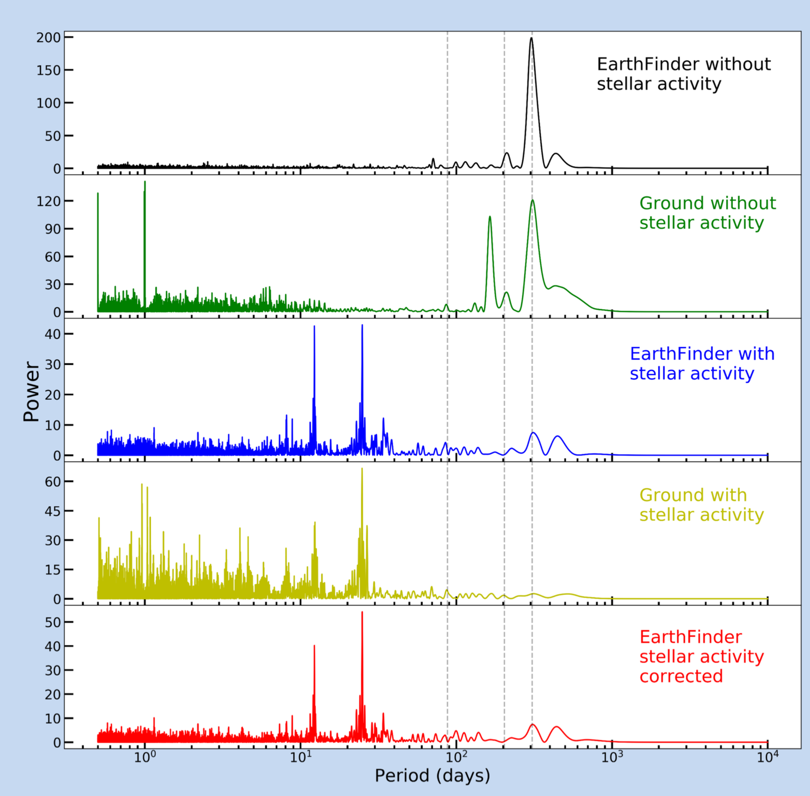
- Telluric absorption is a known bottleneck for achieving < 3 m/s precision in the NIR (Bean et al. 2010)
- Micro-tellurics (< 2% depth) can induce RV errors of 20-50 cm/s; it is unknown how to eliminate their impact beyond 50 cm/s in the visible (Fisher et al. 2016; Cunha et al. 2014, Artigau et al. 2014)
- Modeling telluric contamination in the NIR to the 1% level is difficult (Gulikson et al. 2014; Smette et al. 2015), and residuals would still cause a 0.4-1.5 m/s error for M and K dwarfs at that level (Sithajan et al. 2016)
- Our simulations indicate an optimistic precision limit due to tellurics is ~2 cm/s in the visible and ~30 cm/s at wavelengths longer than 700nm — telluric contamination can only be removed by performing measurements above Earth's atmosphere



Above: RV errors from tellurics as a function of wavelength for the three different correction methods. The RV error is the RMS of of spectral chunk from simulated RVs over a span of 365 days. The red spectrum plotted at the bottom is an illustration of telluric absorption.

Stellar Activity Mitigation

- EarthFinder uniquely provides a combination of optimal sampling, extremely high SNR, and near-UV to NIR capabilities that give us the highest chance of mitigating stellar activity down to the few cm/s level
- Simultaneous measurement of RV color is the only technique that perfectly isolates SA from planet signals
- EarthFinder covers a wavelength out to 2.5 microns with the same precision free of telluric errors, making it the only platform capable of measuring RV color down to ~10 cm/s
- EarthFinder and our ground-based survey are capable of detecting, and recovering the mass of, Earth analogs by modeling stellar activity with Gaussian Processes, but only EarthFinder can recover the phase and eccentricity of our HZ super-Earth analog
- Using a simple toy model with the RV color proportional to the visible stellar activity, we can reduce activity RMS by 62% in the visible with EarthFinder — better than any result from ground-based telescopes modeling SA via line-by-line analysis
- EarthFinder provides absolute flux continuum normalization that is not possible from the ground, which will offer the best platform for line-by-line analysis for activity mitigation from spots, plages and granulation

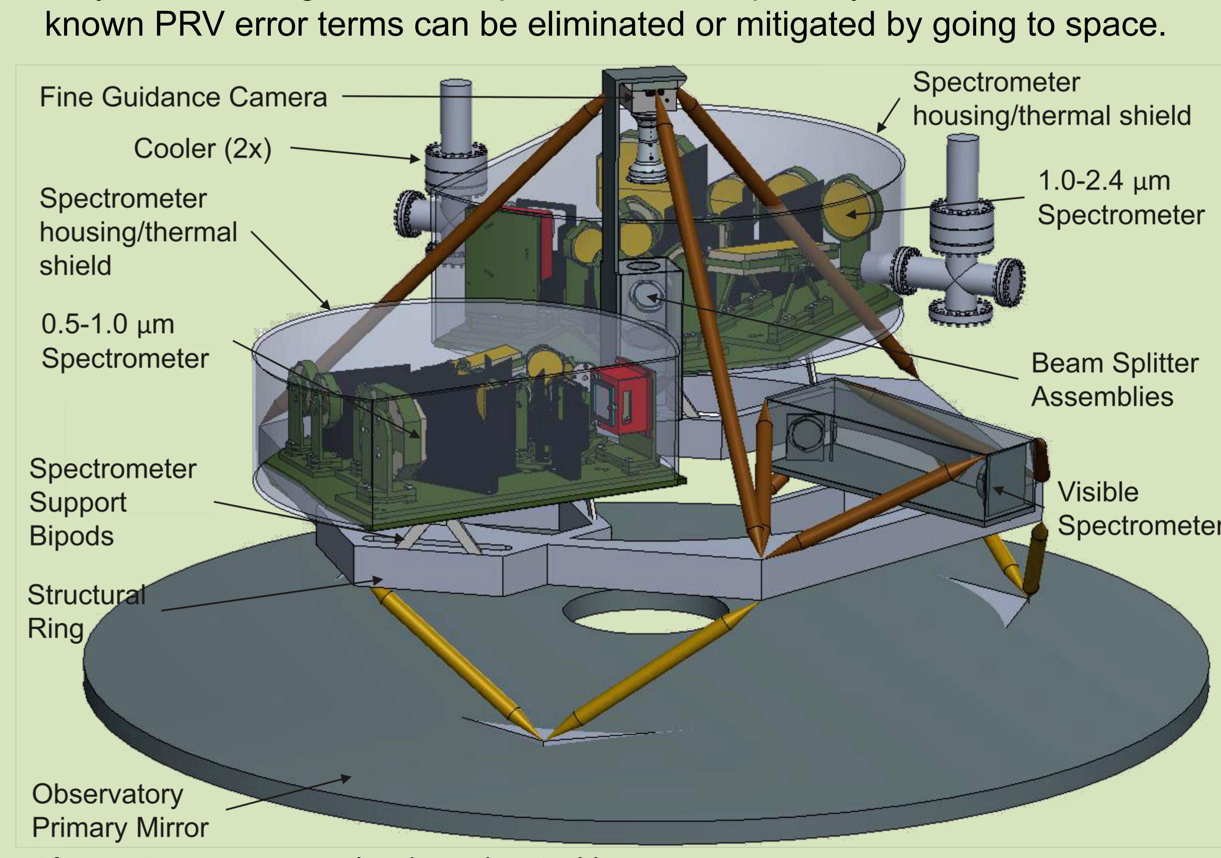


Above: Periodograms of the simulated EarthFinder and ground-based RV time series for HIP 61317. The dashed lines indicate Mercury, Venus, and Habitable Zone super-Earth analog orbital periods.

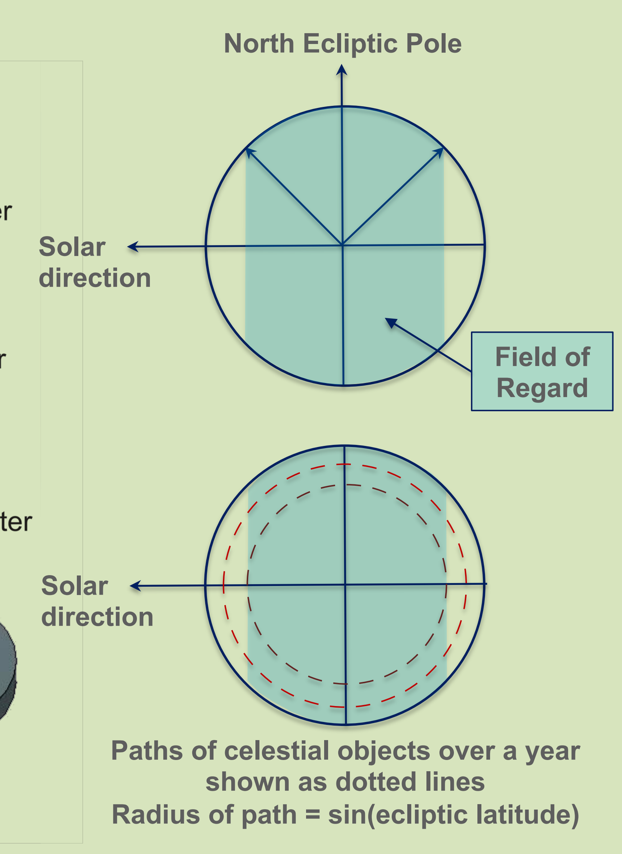
Mission & Instrument

The nominal spacecraft design is based upon the Kepler spacecraft by Ball Aerospace, with a 1.45-m primary, with the starlight coupled into single-mode fibers illuminating three high-resolution, compact and diffraction-limited spectrometer "arms", one covering the near-UV (200-380 nm), visible (380-900 nm) and near-infrared (NIR; 900-2500 nm) with a spectral resolution of greater than 150,000 in the visible and near-infrared arms. A small Solar telescope near the solar panels would also be included to obtain Solar spectra.

The telescope is baffled to minimize the Sun avoidance angle, and has thermal shielding on the spacecraft bus to minimize the anti-Sun avoidance angle and to maximize the instantaneous field of regard. The spacecraft would be placed in an Earth-trailing or Lagrange orbit for minimal velocity changes with respect to the Solar System barycenter during science exposures, with a primary science mission duration of 5 years. Many of the currently known PRV error terms can be eliminated or mitigated by going to space.



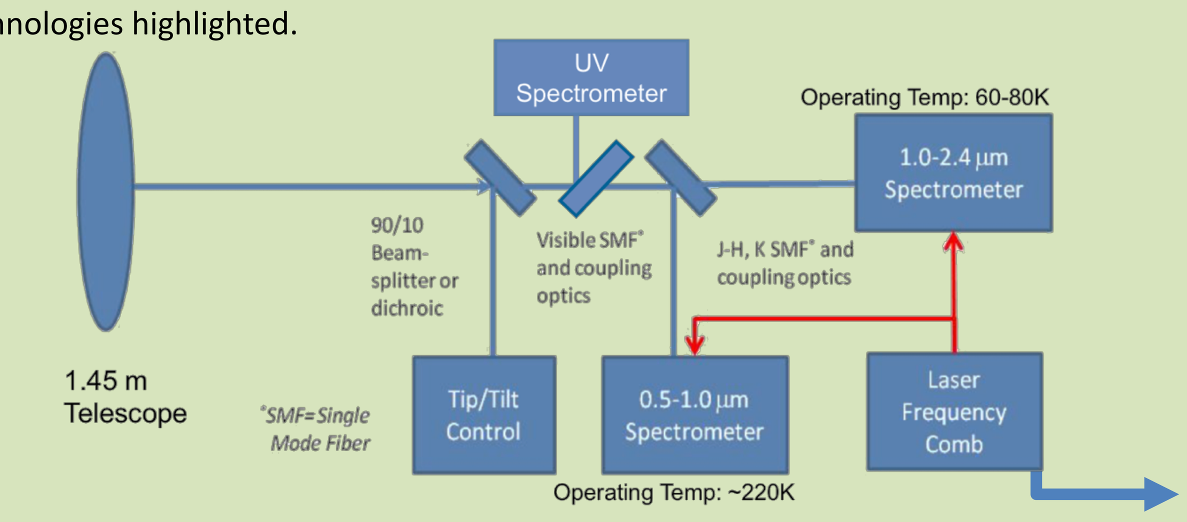
Above: Instrument payload mechanical layout.

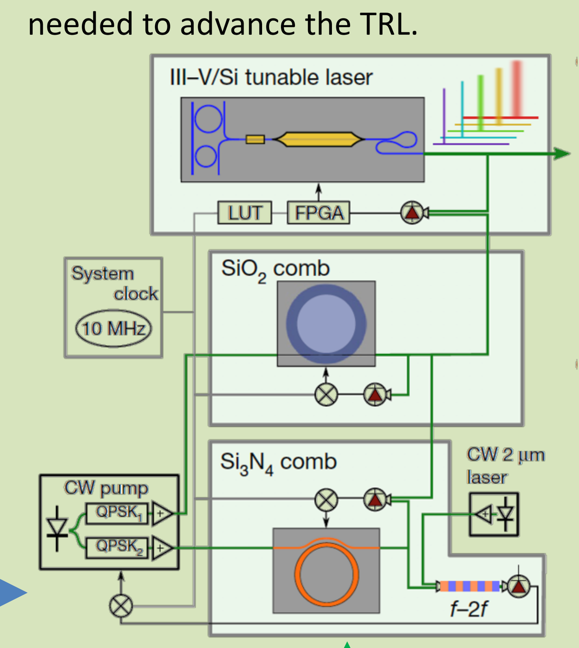


Upper right: Mission field of regard "side" and "top" views. The field of regard extends from 45º from the sun to 135º.

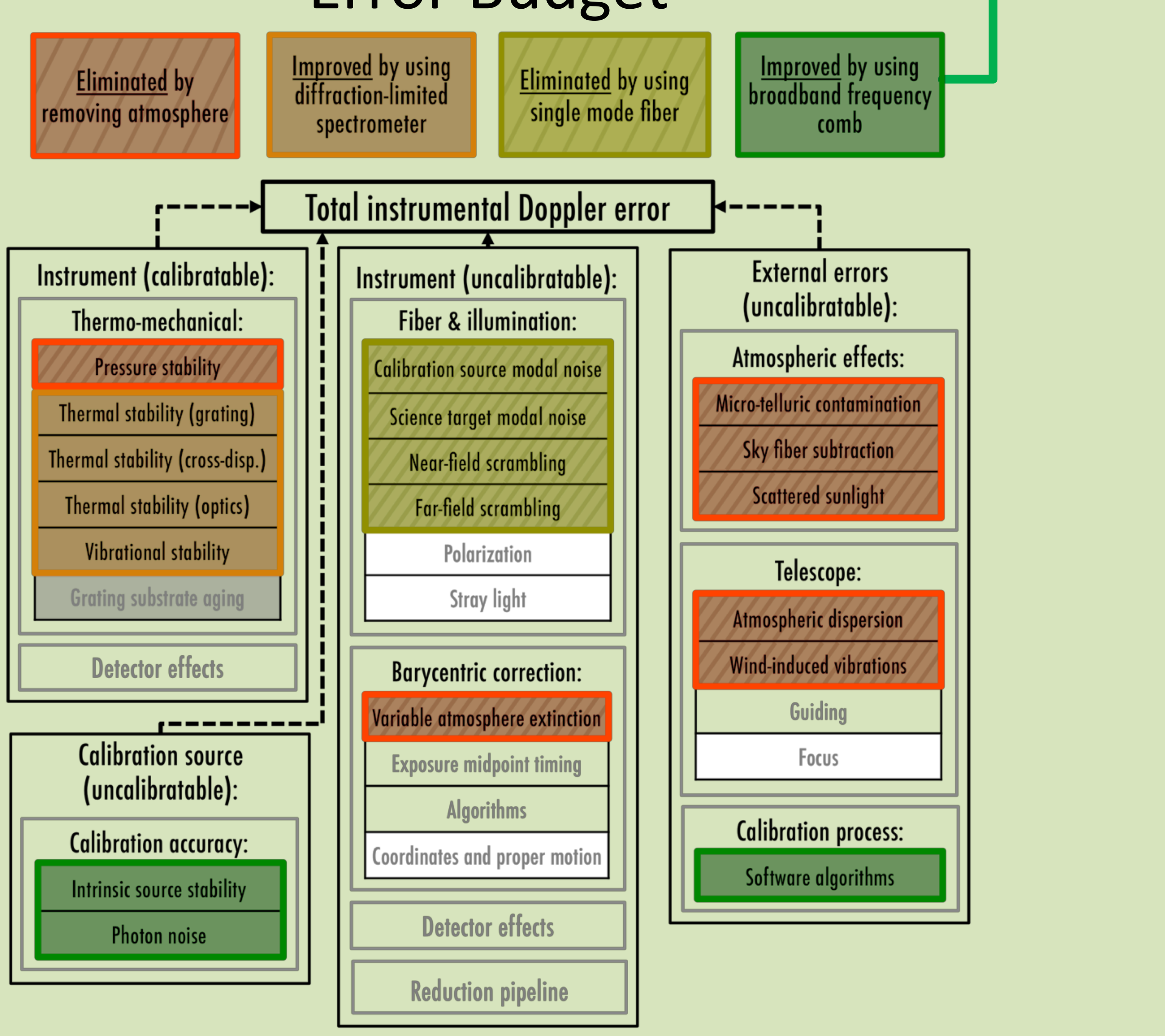
Below: Schematic for a high-rep rate microresonator frequency comb (Lezius et al. (2016). Further R&D is needed to advance the TRL.

Below: Schematic block diagram of telescope and instrument, with key technologies highlighted.





Error Budget



Above: Mission error budget: Highlighted terms represent errors that are either significantly reduced, or entirely eliminated, by (1) removing the atmosphere (red), (2) using a compact, diffraction-limited spectrometer (orange), (3) delivering light to the instrument using a single-mode optical fiber (yellow), or (4) using a broadband optical frequency comb calibration source. **Removing or significantly reducing these instrumental error sources opens an entirely new discovery space.**