HARPS 3 and the push to 10cm/s RV accuracy

Presented by Clark Baker on behalf of the HARPS3 consortium and the Terra Hunting Experiment

Abstract and Introduction:

The Terra Hunting Experiment (THE) will conduct the most intensive search for nearby Earth-twins to date. It will utilise a nightly radial velocity (RV) observing strategy over a 10 year period on a carefully selected target list, with the aim of discovering ~Earth-mass exoplanets around G- and K-type stars, with orbital periods of 100+ days. In order to achieve this objective, an ultra-stable spectrograph capable of measuring RVs with a consistent instrumental accuracy on the order of 10cm/s is required. To meet this requirement, an upgraded version of the proven and successful High Accuracy Radial-velocity Planet Searcher (HARPS) spectrograph is being developed: HARPS3, an R≈115,000, fibre-fed, Echelle spectrograph with an operational wavelength range of 380–690 nm and a deployable/integrated, dual-beam, full-Stokes polarimeter for spectropolarimetry. HARPS3 will be coupled to an upgraded and roboticised 2.54m Isaac Newton Telescope (INT) and will utilise a robust series of stability measures in order to achieve its required ~10cm/s stability.

Spectrograph Optical Layout:

The optical design of the HARPS3 spectrograph is based on an iteration of the proven (<0.6m/s long term precision) HARPS and HARPS-N design.

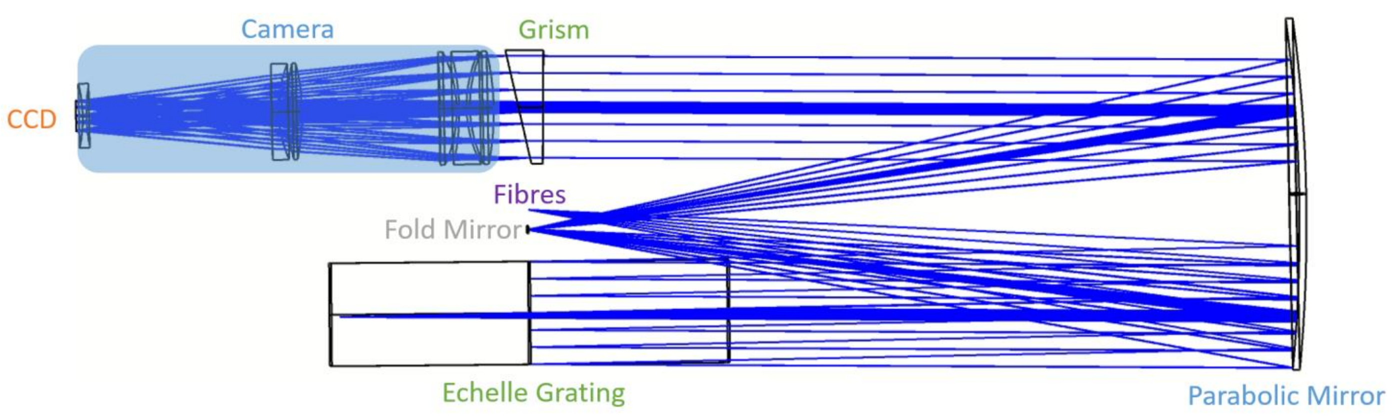

Figure 1: Annotated optical schematic of the HARPS3 Spectrograph.

The instrument is coupled to both the telescope and calibration unit/polarimeter via two 70µm, 0.12NA multi-mode octagonal fibres. These fibres are input into the spectrograph through a micro-lenslet, producing an F/8 dispersing beam. The beam is collimated by a 1560mm focal length, off-axis parabolic mirror, whereby it is dispersed by an R4, 31.6 gr/mm, 2x1 mosaic Echelle grating. The dispersed beams are then focused by the parabolic mirror, reflected off of a fold mirror and re-collimated by the opposite side of the parabolic mirror. These collimated beams are cross-dispersed by a 13.235°, FK5 grism with a 257.14 gr/mm diffraction grating set onto the rear surface. The Echelle spectrum is imaged onto the CCD (e2v CCD231-84-0-G57) with a custom 729mm focal length camera lens.

The camera is an iteration of the HARPS design, which has been re-optimised to compensate for the replacement of obsolete glasses. The camera is currently at the FDR stage and spot performance of the nominal optical design appears to be comparable to, or surpass, that of the HARPS-N camera.

For stability, the Echelle grating substrate is constructed from Zerodur Class 0 SPECIAL, which has a CTE = 0 ± 0.010×10^{-6} ppm/K and has been aged to minimise drift.

Cassegrain Fibre Adapter System:

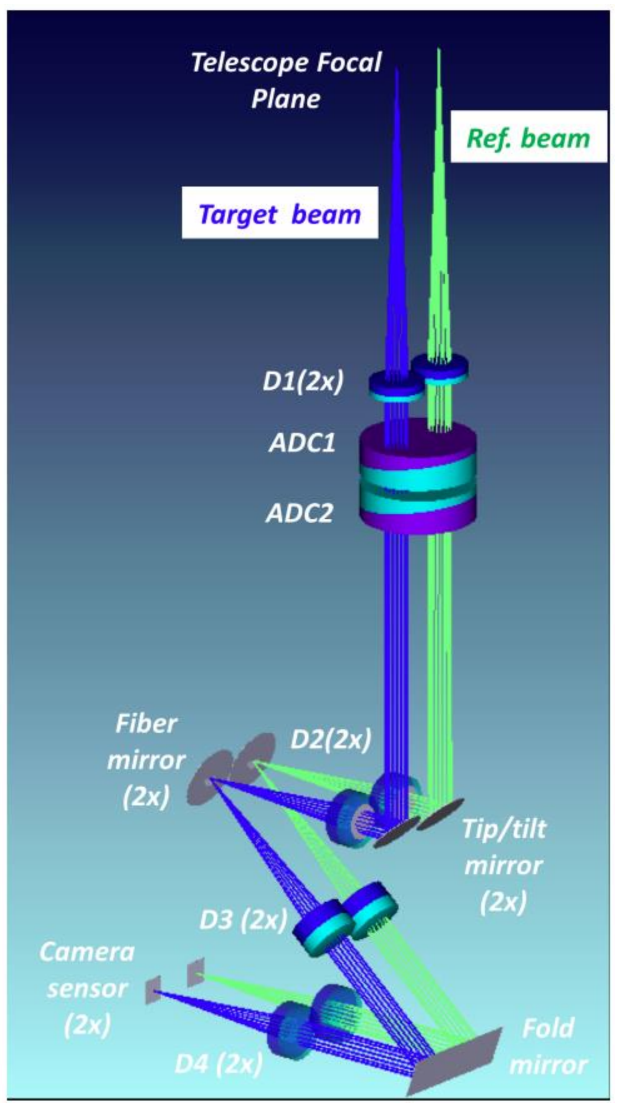

Figure 2: Optical schematic of the Cassegrain Fibre Adapter System.

The Cassegrain fibre adapter is attached to the telescope at the Cassegrain focus and enables the coupling of the telescope to the optical fibres that feed the spectrograph. This unit contains the atmospheric dispersion corrector (ADC), a tip/tilt system, the calibration light projection optics, the polarimeter optics and a fibre selector mechanism.

Optical Fibres and Coupling:
Uniform output illumination of the optical fibres is critical to the RV precision of the spectrograph. To ensure this, a robust scrambling solution applying octagonal fibres, double scramblers and a fine pointing system with 0.05′′ RMS accuracy (over the length of an exposure) is applied. To reduce spectral fringing below the 10^{-5} level, no parallel surfaces are applied in the fibre adapter optical path.

Polarimeter:
The polarimeter is a deployable, Full-Stokes, dual-beam polarimeter with low channel cross-talk and will enable further study of stellar activity.

Environmental Control System:

The spectrograph is housed in a thermally stable room with increasing degrees of thermal control provided by a nested active thermal enclosure system. These thermal enclosures, called HTE1, HTE2 and HTE3, each increase the level of thermal stability by an order of magnitude, with the innermost, HTE3, being stable to ±0.01K. Within HTE3 is a custom vacuum vessel which houses the main spectrograph optics and detector; this will maintain an internal pressure of ~5×10^{-3}mbar.

Further to the main vacuum vessel, the CCD will be housed in a cryostat based on a miniaturised version of the ESPRESSO design. This is planned to achieve ~1mK RMS stability with a vacuum pressure inside detector unit of ~2×10^{-6} mbar.

HARPS3 will have a full suite of environmental sensors installed throughout the spectrograph. These include pressure sensors, accelerometers and temperature sensors near key components; which will enable the detection of temperature gradients. These sensors will track the mechanical/thermal changes of the instrument and enable us to characterise their effect on the stability performance of the spectrograph.

Roboticised Isaac Newton Telescope:

The Isaac Newton Telescope (INT) is a 2.54m equatorial-mount telescope located in the Northern hemisphere on the island of La Palma in the Canary Islands. For the Terra Hunting Experiment, which will conduct an intensive search for ~Earth-mass exoplanets in 100+ day period orbits around G- and K-type stars over a 10 year long observing strategy, the INT will be upgraded and roboticised to facilitate the efficient collection of data. **Check out the poster by Annelies Mortier for more information on the Terra Hunting Experiment!**

The INT upgrade will include a thorough refurbishment of the telescope and consist of (amongst other items) renewal of the pointing and tracking systems, dome drive systems, control systems and an automated scheduling system to facilitate complete robotic operation of the telescope; enabling optimal and flexible observation.

The site has a median seeing condition of ~0.8 arcseconds. The INT, however, currently only achieves a median seeing of ~1.3 arcseconds. It is thought that improvements in ventilation and guiding will enable sub-arcsecond imaging performance to be achieved.

CCD Mapping:

A Doppler shift of 10cm/s is equivalent to a shift of ~1/1000 pixel on the detector, we aim to characterize the effective pixel position to this millipixel level in order to provide an increased precision wavelength solution for accurate calibration.

To achieve this, an experimental set-up is applied which uses a laser that feeds two optical fibres and generates an interference pattern on the CCD. By shifting the phase between the two fibres it is possible to sweep the interference fringes across the detector surface. Once this is done over a phase of 2π, with regular frames taken at different phases, a column of intensity data from a single pixel will yield a sine wave which contains pixel displacement information. By comparing the phase difference between the measured intensity sine wave and a model fit to the entire sensor, it is possible to calculate the component of the pixel displacement in the direction of the wavevector.

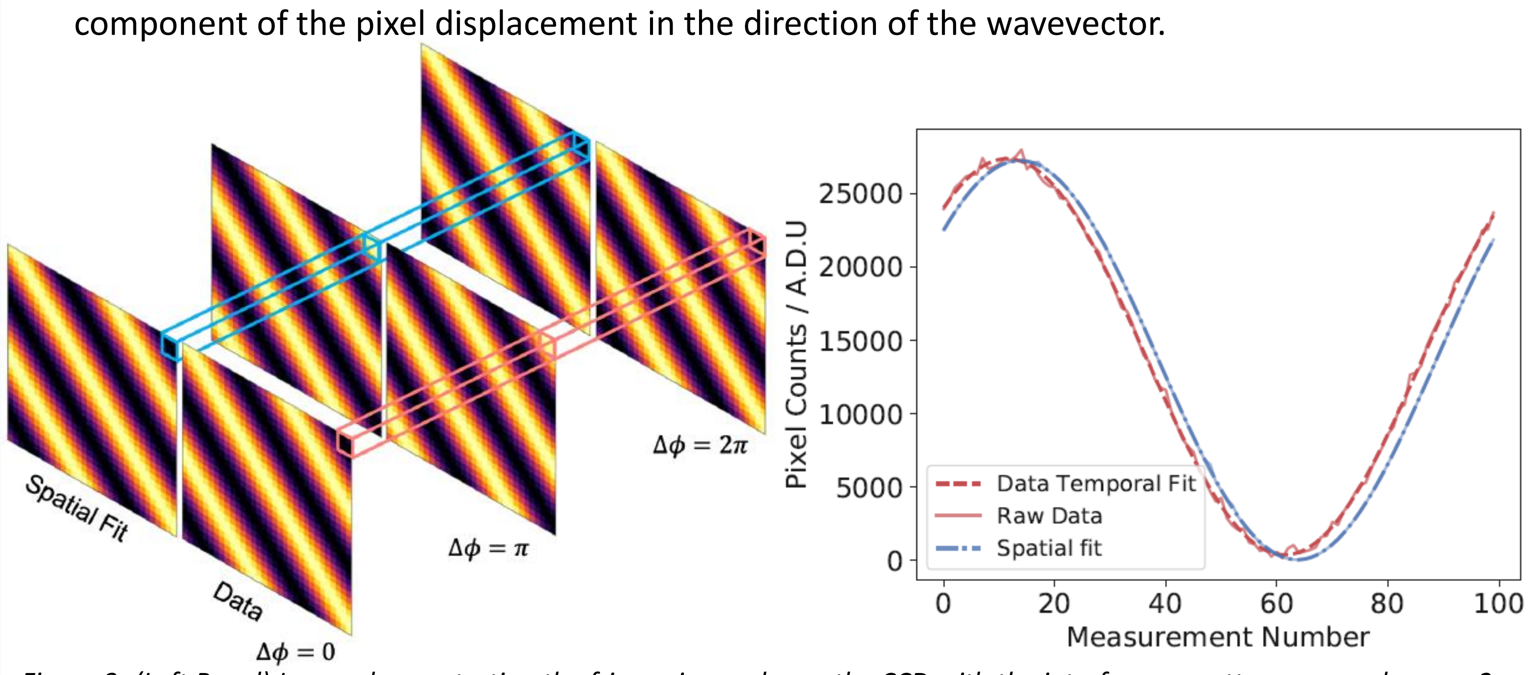

Figure 3: (Left Panel) Image demonstrating the fringes imaged over the CCD with the interference pattern scanned over a 2π phase change. (Right Panel) Plot of measurement number over a 2π phase change against counts detected by the pixel for both the data collected by the pixel and the spatial fit of the fringes for the whole CCD; the difference in their phase holds position information.

Calibration:

Full sets of calibration frames are scheduled to be taken at the beginning and end of every night. HARPS3 also has a secondary fibre for simultaneous reference.

The main body of the calibration unit will be housed in the Coudé room with the spectrograph. Light from the calibration sources are fed into the spectrograph via the Cassegrain fibre adapter. The calibration unit has 8 switchable slots and will house a series of calibration lamps; these include a ThAr lamp (+ spare), UrNe lamp and a Halogen lamp (+ spare); for flat fielding. External to the calibration unit but also to be coupled to one of the 8 slots is a Fabry-Perot etalon.

Further to these calibration sources, under development for HARPS3 is a laser frequency comb system with 1-2cm/s RV accuracy and a broadband (380nm-690nm) wavelength range. Design is also underway for a solar telescope, with polarization capability, that would similarly use one of the 8 calibration slots.

Performance:

HARPS3 will achieve a resolving power of R~115,000 across an operational wavelength range of 380–690 nm and is expected to see first light in **2023**!

It is predicted that HARPS3 at the INT will have a photon limited RV error of ~0.25 ms^{-1} for a 15 minute exposure of a G = 7.5 G8V star in 1.2 arcsecond seeing conditions. Short term instrumental error is expected to be <10cm/s and it is thought that the instrument's sensor suite and calibration strategy will allow the tracking of systematics and long term drift.

The throughput of some optical components are still subject to change, as they are under the manufacture and testing stages, however, with current data the predicted efficiency of HARPS3 (not considering slit efficiency) averages at ~10%, with a minimum of ~5% at 380 nm and a maximum of ~13% at 550 nm.

The HARPS3 Consortium and THE contains:
The University of Cambridge (PI), University of Exeter, Geneva University, Instituto de Astrofísica de Canarias, The Netherlands Research School for Astronomy, Uppsala University, Flatiron Institute, Princeton University, Queen's University Belfast, the University of Oxford, and the University of Warwick.

References: *Thompson et al. (2016), Hall et al. (2016), Thompson et al. (in prep).*