Characterising Effects of Pixel-positioning Error for Extreme Precision Wavelength Calibration with a Laser Frequency Comb

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Introduction and Motivation

- Photolithographic CCD fabrication results in per-pixel positioning errors of around **1-3% of a pixel width**, previously estimated to induce mean radial velocity (RV) estimation errors of order 1 cm s^{-1} (Halverson et al., 2016).
  - Generally neglected: state of art presently $\sim$ 1 m s^{-1}.
  - **No reliable extant characterisation**
- The EXtreme PREcision Spectrometer (**EXPRES**) aims for RV precision of order **10 cm s^{-1}**
  - May be sensitive to errors of this magnitude

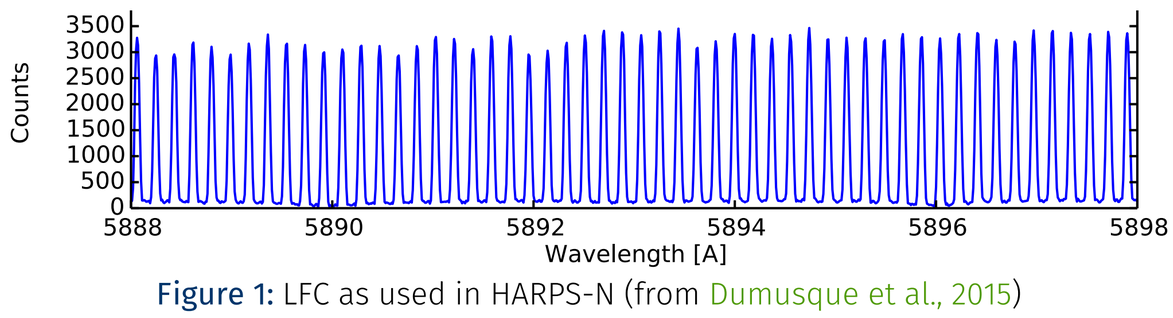


Figure 1: LFC as used in HARPS-N (from Dumusque et al., 2015)

- EXPRES will use a **laser frequency comb** (LFC) for wavelength calibration: effect of such errors *should* be accurately characterised.

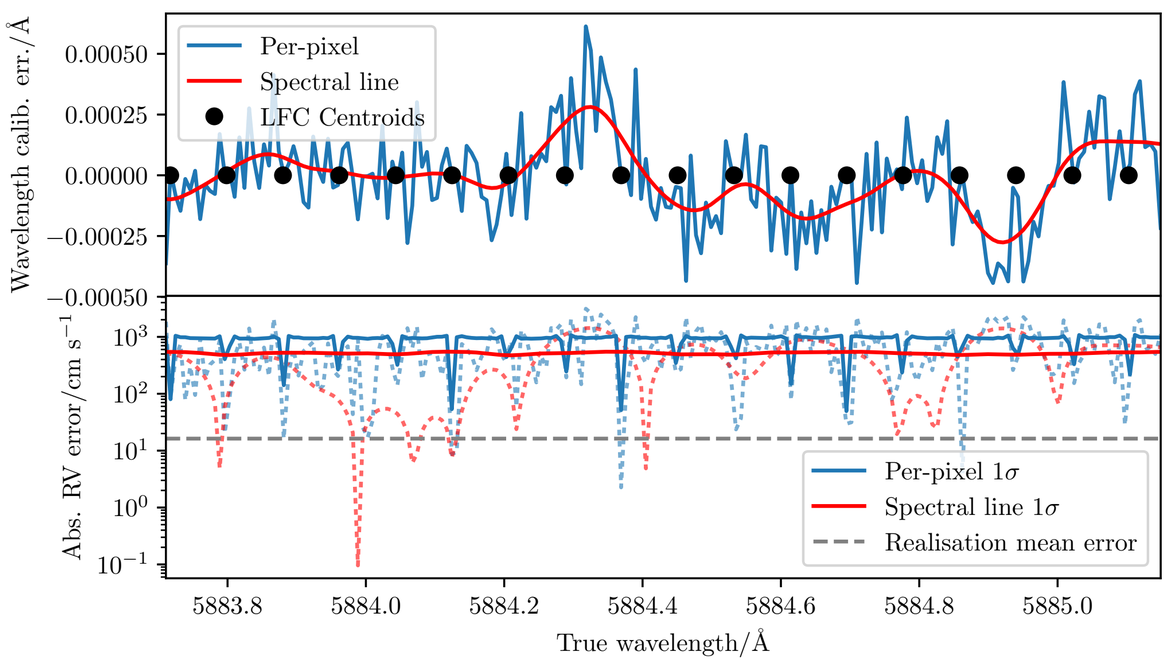
Numerical Experiment

- Generate realisations of error by perturbing pixels from idealised positions
- Calibrate wavelength solutions by interpolating between pixel locations of LFC centroids against known wavelengths.

Random Scatter

- Pixel-position error with white (fig. 2) and red noise characteristics return similar results (RMS 2% pixel width).
- Wavelength-calibration (and so RV estimation) error is incurred in pixels **between LFC centroids**, if constant spacing assumed.
- For spectral lines of FWHM $\sim$ 10 px, local RV error is convolution of per-pixel error against line profile.

Figure 2: Wavelength Calibration and RV Estimation Error from Pixel-Position Error



- RV estimation error **comparable to precision goal** ($\sim$ 10 cm s^{-1}) even when averaged over échelle order.
- RV estimation error **does not change** when averaged over spectral line (rather than pixel) positions.

References

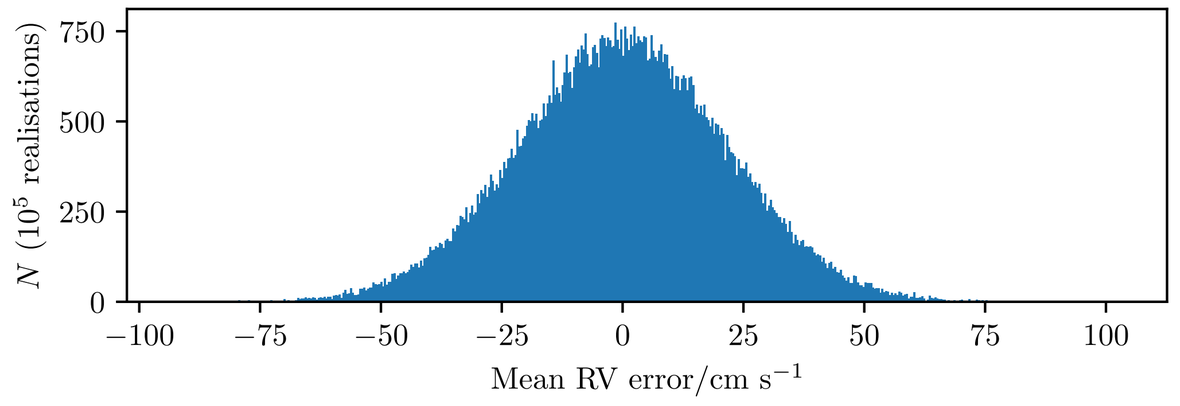
Dumusque, X., Glenday, A., Phillips, D. F., et al. 2015, The Astrophysical Journal, 814, L21

Halverson, S., Terrien, R., Mahadevan, S., et al. 2016, A comprehensive radial velocity error budget for next generation Doppler spectrometers

Posterior Distribution

- We characterise the effect this might have on EXPRES by sampling the posterior distribution of the mean RV errors (fig. 3).

Figure 3: Posterior distribution of mean RV error from 10^5 realisations

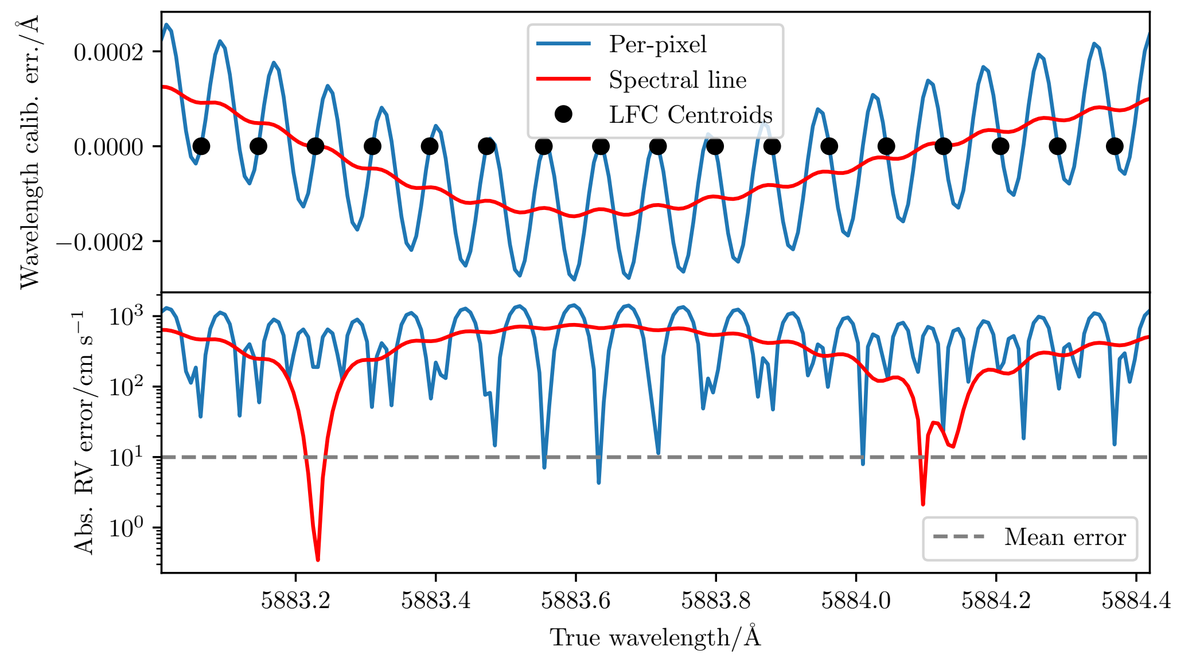


- Gaussian shape: Lyapunov CLT condition holds.
- RMS mean error $\sim$ 25 cm s^{-1}: **comparable to precision goal**!
  - Much larger than extant characterisations

Nonrandom Errors

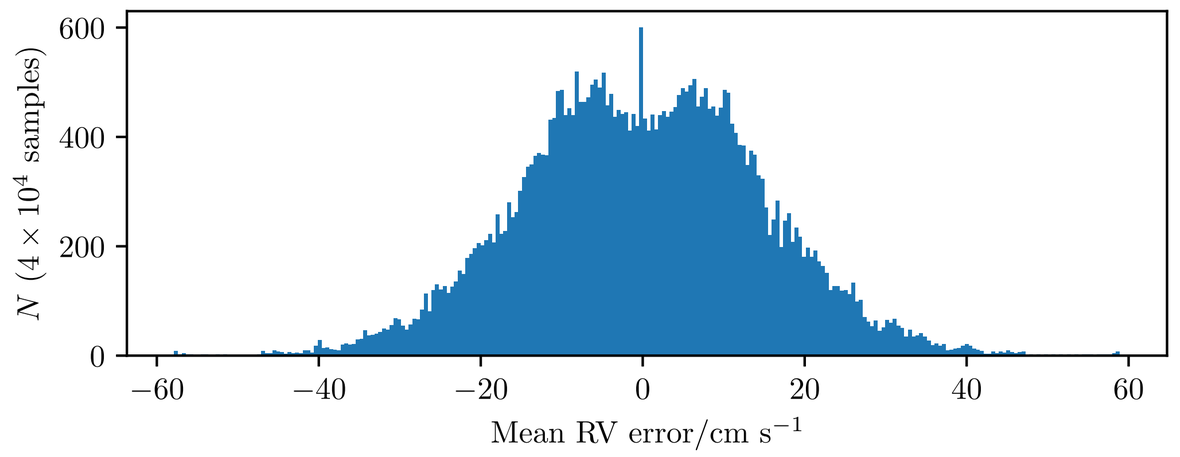
- Fixed-pattern periodic positioning error at too high frequencies cannot be Nyquist-sampled by the LFC and calibrated away.

Figure 4: RV error from sinusoidal pixel displacements



- Spread of mean errors broadly similar (although distribution is nongaussian, fig. 5)

Figure 5: Distribution of RV erors from uniformly sampling parameter space



Mitigation Strategy

- Averaging over orders may suppress random error by factor of 4
  - **Cannot be neglected**, but good start
- The EXPRES CCD will be interferometrically characterised at JPL
  - Individual pixel positions to within 10 nm, or $\sim$ 0.1% of a pixel width: error suppressed by an **order of magnitude**.
- Caveat: **This is only one error term out of many**.