Constrained modeling of instrumental drift in precision Radial Velocity Spectrometers and Wavelength Calibration: Application to HPF

Joe Ninan[1]*, Ryan Terrien[2], Arpita Roy[3], Chad F. Bender[4], Suvrath Mahadevan[1], Gudmundur Stefansson[5], Kyle Kaplan[6], Andrew J Monson[1], Samuel Halverson[7], Paul Robertson[8], Christian Schwab[9], The HPF & NEID team

[1]The Pennsylvania State University, [2]Carleton College, [3]California Institute of Technology, [4]University of Arizona, [5]Princeton University, [6]NASA Ames Research Center, [7]Jet Propulsion Laboratory, [8]University of California, [9]Macquarie University

Motivation

For precise measurement of the radial velocity change in a star, the precision of the wavelength solution is 4 orders more important than accuracy of the wavelength solution. Since the absolute wavelength solution model of a multi-order echelle spectrographs require a large number of parameters, it is better to track the change in wavelength solution over time instead of refitting the complete wavelength solution without any constrains. For stabilized spectrographs like The Habitable-Zone Planet Finder (HPF) and NEID, these changes in wavelength solution are significantly low order and can be modeled with only a few parameters. Table 1, shows an example of low order changes to dispersion solution we expect from various physical mechanisms in HPF or NEID.

Table 1 Physical mechanism versus type of distortion in dispersion solution

Physical Mechanism	Dispersion solution change
Input slit motion in dispersion	Wavelength Shift
Input slit motion in cross-dispersion	Velocity Shift
Shrinking of Grating	Velocity Shift
Moving of detector in focal plane	Pixel shift
Camera F/# change	Scaling

Master Wavelength Solution

Our Laser Frequency Comb (Metcalf et. al. 2019) cover the entire bandpass of 0.8 to 1.24 microns in HPF. Hence, we use LFC as our primary wavelength calibrator for all HPF echelle orders. The overall procedure is fitting a polynomial model to the individual centroids of the LFC emission lines. Following points list the subtleties in fitting a model to LFC line centroids.

- A high S/N master template of LFC is created by averaging while iteratively correcting the drifts over a few days.
- Five degree Legendre polynomial has enough flexibility to fit the dispersion wavelength solution in each of the HPF echelle order.
  - Reason for Legendre: *The dense uniform sampling of the LFC in scaled pixel space (-1 to 1) preserves the orthogonal properties of the Legendre polynomial coefficients.*
- Faint continuum background inbetween LFC modes is interpolated and subtracted before fitting Gaussian profiles.
- Gaussian was fitted without photon noise weights to prevent the centroid bias being sensitive to the particular LFC line's flux.
  - Reason: *HPF line spread function (LSF) is asymmetric on the red side of orders, which biases the Gaussian centroids. Unlike ThAr, LFC line flux is not stable, hence if symmetric weights are not used, it will result in flux dependent bias. (See Fig 1)*

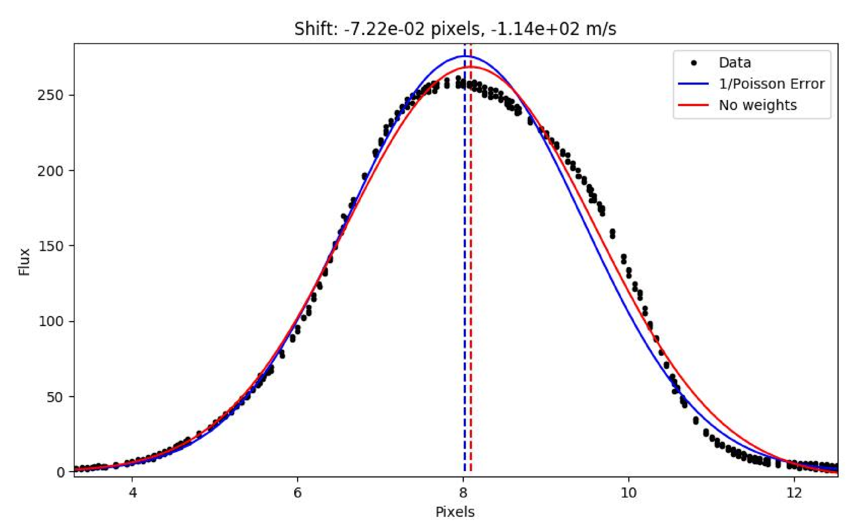


Fig 1: Shows the super resolution LSF obtained by phase folding LFC. Bias in Gaussian centroid is insensitive to line flux only for un-weighted least square fit.

Drift Model for HPF

By studying the distortion in the wavelength solution of HPF over multiple years, we could identify the following distortions to the dispersion solution.

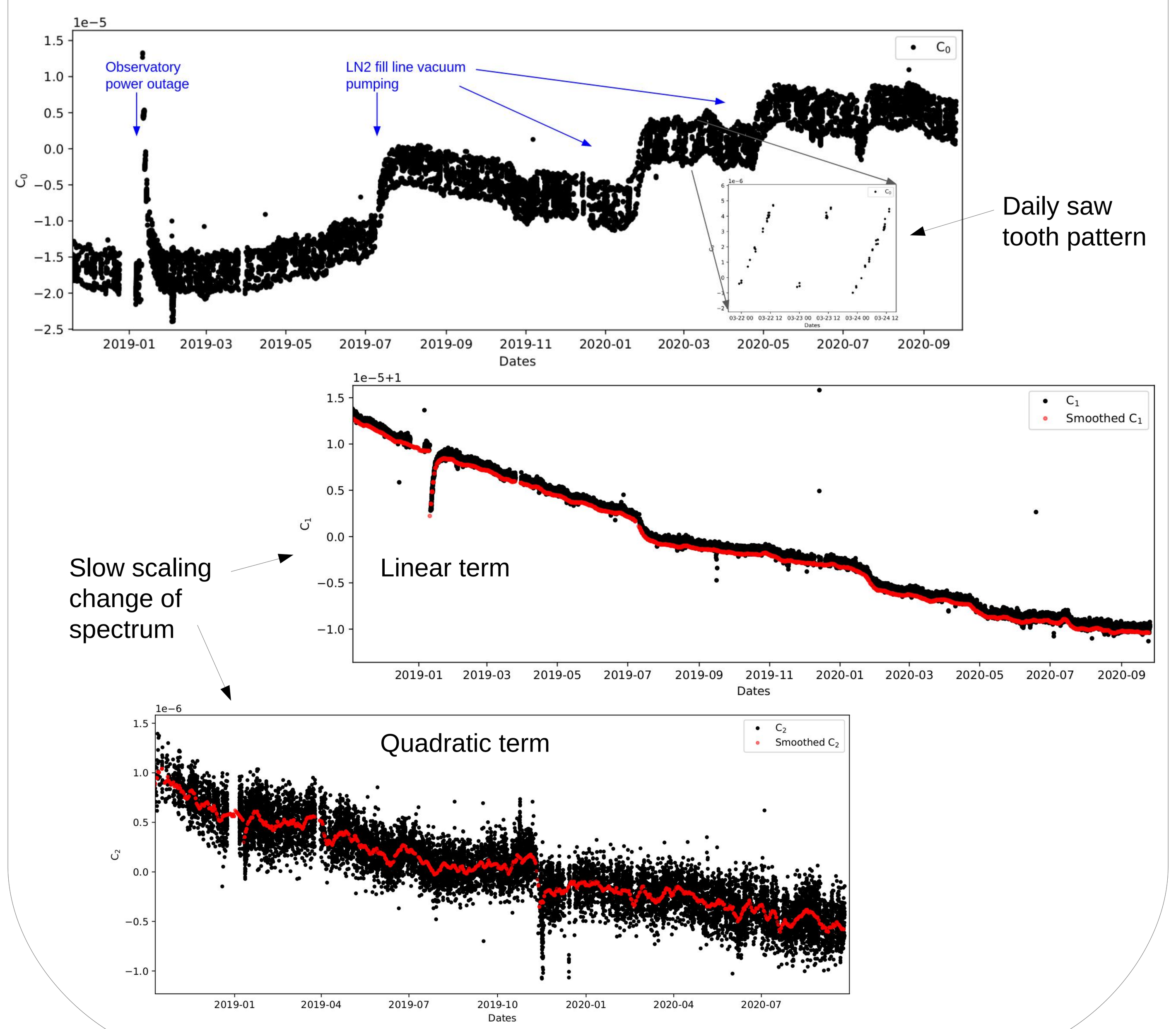
- Periodic shift in pixel space, corresponding to daily LN2 fill of the instrument. The periodic pattern is a clean saw tooth.
- Very small change in the scale of the spectrum over timescale of weeks.
- Slow pixel offset in each readout channel in the readout direction during the 2019 January to 2020 November period. (See Terrien et. al SPIE #11454-146 for more details on this H2RG effect)

Step 1: Calculation of Coeffs

The high S/N master template LFC created for Master wavelength solution is fitted by least square algorithm to obtain an independent estimate of the following terms for every LFC observation. (All the calculations are in the scaled pixel domain [1:2048 → (-1:1)] for orthogonal properties)

- C_0: Pixel shift
- C_1: Linear scaling of the wavelength solution
- C_2: Quadratic scaling of the wavelength solution

Plots below show each of these coefficients evolution over time.



Step 2: Refine the Coeffs

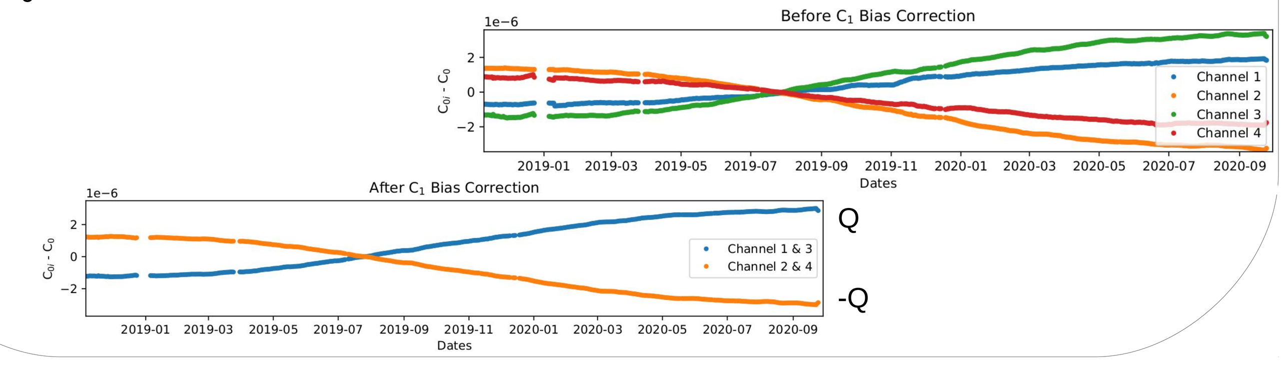
C_1 and C_2 terms evolve only in the timescale of weeks. Hence, we smooth these coefficients using a running window of 5 days.

Keeping the refined C_1 and C_2 terms for each day as constants, the C_0 term is re-fitted for all the LFC frames. To measure the readout channel effect, C_{0i} term for each of the four readout channel is also calculated separately at this stage.

Step 3: Coeff bias corrections

The slow pixel offset in each readout channel in the readout direction during the 2019 January to 2020 November period. (See SPIE#11454-146 for more details) biases the C_1 linear drift coefficient, as well as the readout channel level C_{0i} terms.

Since we know the relative strengths of each readout channel's pixel shift effect, we can analytically calculate the bias and correct the daily C_1 term as well as the readout-channel level coeffs C_{0i}. C_{0i}-C_0term is also smoothed using a running window of 5 days.

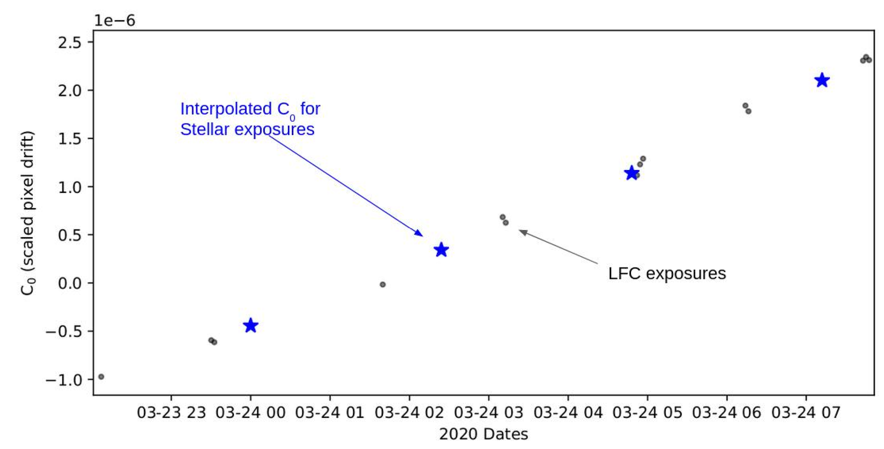


Step 4: Interpolating C_0

Instrumental drift is thus parametarised by 3 coefficients C_0,C_1,C_2 for changes in HPF optics, and an extra Q term for the read-out channel effect on the H2RG detector. For any given night, C_1,C_2 and Q are constants, and only C_0 term changes linearly with time.

- C_0(t) term for the epoch of observation of a star is obtained by interpolating to the epoch t from all the LFC observations taken that night. The individual estimated from the LFCs of the same night is weighted by inverse square of the time elapsed between the LFC and star observation.

Figure shows the interpolation of the C_0 to the epoch of any stellar observations.



Wavelength Calibration

The master wavelength solution is transformed by the final coefficients C_0,C_1,C_2 and Q derived in the above steps to obtain the HPF wavelength solution for any epoch.

The coefficients calculated for HPF Cal fiber was found to be consistent with the calculation from Science fiber, enabling us to calibrate Science fiber using the Cal fiber LFC.

For nights without LFC, we use our passively stabilized Fabry Perot Etalon to estimate the C_0.

While the model we presented here is specific to HPF, the same philosophy can be applied to any stabilized spectrographs whose instrumental drifts are of low order.

This work was partially supported by NSF (AST 1006676, AST 1126413, AST 1310885) and Heising-Simons Foundation

SPIE,2020
*jpn23@psu.edu