Correcting crosshatch pattern in H2RG for high precision near-infrared RV in HPF

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Introduction

- The Habitable-Zone Planet Finder (HPF) is a fiber-fed near-infrared (0.8 to 1.24 μm) ultra stable precision radial velocity (RV) spectrograph commissioned on the 10-m Hobby-Eberly Telescope (HET), McDonald Observatory, Texas, USA. HPF uses a 1.7 μm cutoff H2RG (Hawaii-2RG HgCdTe 2048x2048) array as detector.
- Near-infrared H2RG detectors suffer from various artifacts compared to optical CCDs, which need to be corrected for precision measurements in stellar spectrum.
- We have demonstrated intrinsic calibration precision as low as 6 cm/s and the measurement of differential stellar RVs at 1.53 m/s sigma over months-long timescales, which is unprecedented in the near infrared wavelength region.

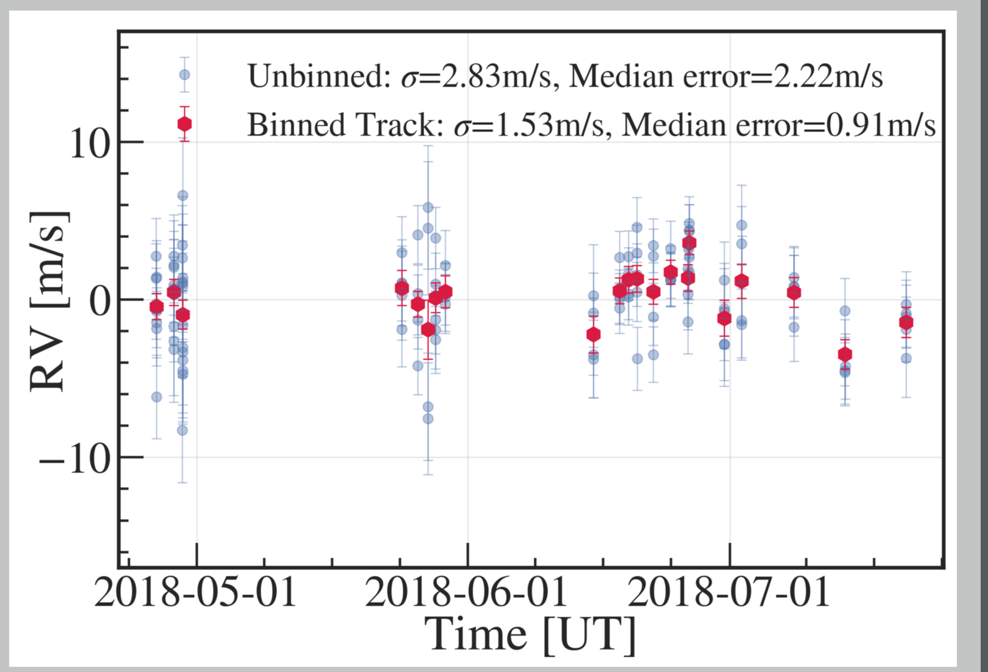

Figure 1: 1.53 m/s sigma over months-long observation of Bernard's star achieved with HPF

Crosshatch pattern in H2RG

- A sample region of the HPF's H2RG detector containing crosshatch pattern is shown here. These are believed to be intra-pixel quantum efficiency (QE) variation due to lattice defects in the HgCdTe crystal layer (Hardy et. al. 2008, Shapiro et. al. 2018).
- Since the conventional flat correction only normalizes the average QE of each pixel, these intra-pixel structures result in an intra-pixel flux distribution depended gain variation.

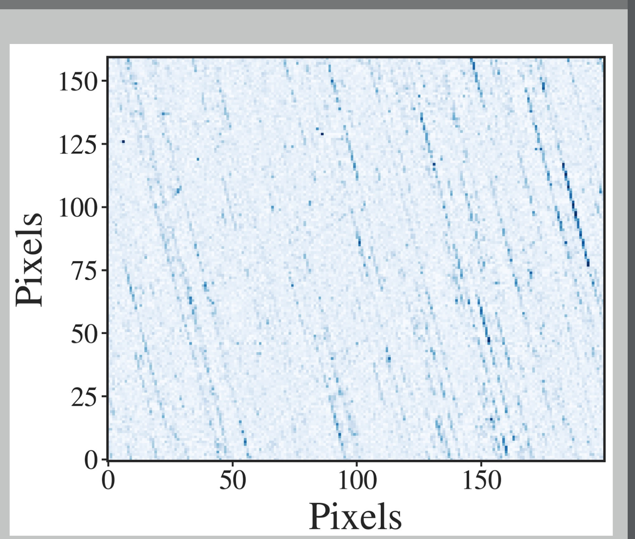

Figure 2: A sample crosshatch pattern region in HPF

Measuring intra-pixel structure from the flat image

- A map of the crosshatch pattern on the detector (shown in Fig 2) was created by high pass filtering a smoothly illuminated flat.
- The angle of the crosshatch pattern is measured precisely from the 2D power spectrum of this image. This was measured to be 14.8 degrees for HPF's detector.
- Figure 3 shows a zoom of a typical 14.8 degree cross hatch QE variation pattern in HPF. The defect moves 3.8 rows before it jumps to next column.
- In this plotted region, the pixel averaged relative QE of the middle three pixels (where the defect is fully contained inside a pixel boundary) is $\sim$ 88%.
- In the region labelled as B, the defect is moving from column 2 to 3 across two rows. The sum of the QE drop in the crossover pixels combined is $\sim$10% for both the rows.
- Region labelled as A has the defect moving from column 3 to 4 within a single row. The sum of the QE drop in both those crossover pixels combined is $\sim$11%.

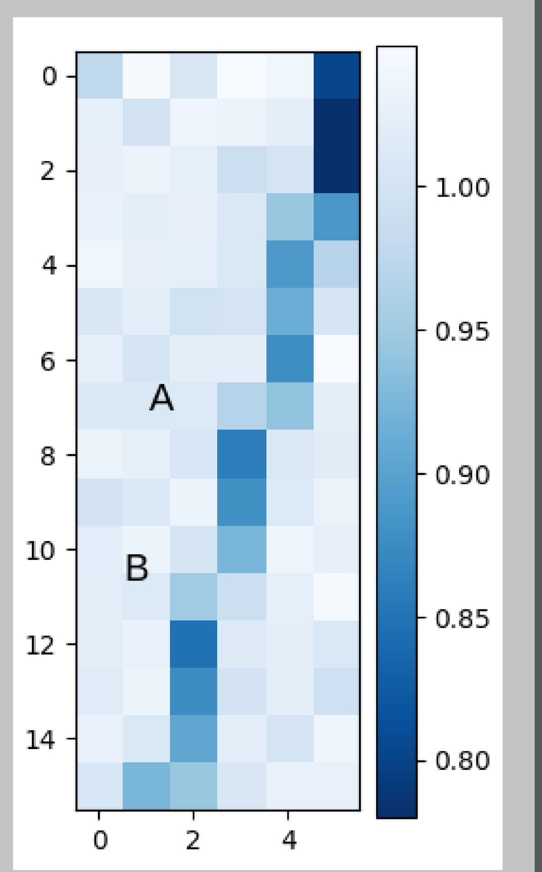

Figure 3: Zoom of a typical QE variation due to lattice defect

- The shortest and longest cross over length scale (in units of rows) from one column to adjacent column constrains the width of the defect. In this case, the width of the crosshatch defect shown in Figure 3, can be constrained to be $\sim$1/3.78 of a pixel. i.e. $\sim$5 μm.
- Using this width constraint and the net drop in QE of the pixel–which fully contain the defect inside its pixel boundaries, we obtain the QE of the region inside the defect to be $\sim$54% relative to outside region.
- The method outlined above have the following caveats
  - The QE drop inside the defect varies across the defect.
  - The absolute gain differences of each neighboring pixel's amplifier limits the accuracy of this QE variation analysis. One has to make an accurate pixel-by-pixel gain-map using individual pixel's photon transfer curve, and divide that out from the flat shown here.
  - The simple line width model of the defect's intra-pixel QE is a simplification, and might not be fully valid near pixel boundaries or depletion region boundaries.
  - The relative neighboring pixel QE analysis outlined here is difficult in the regions with high density of crosshatch patterns.

Slit width averaging in HPF

- To average out pixel inhomogeneities, HPF was designed to image the fiber slit across 2.5×9.5 pixels as shown here. For enabling this averaging, the rectangular slit was rotated and aligned vertically along the pixel columns. However, there are residual effects from the edge pixels inside a trace which need to be corrected.

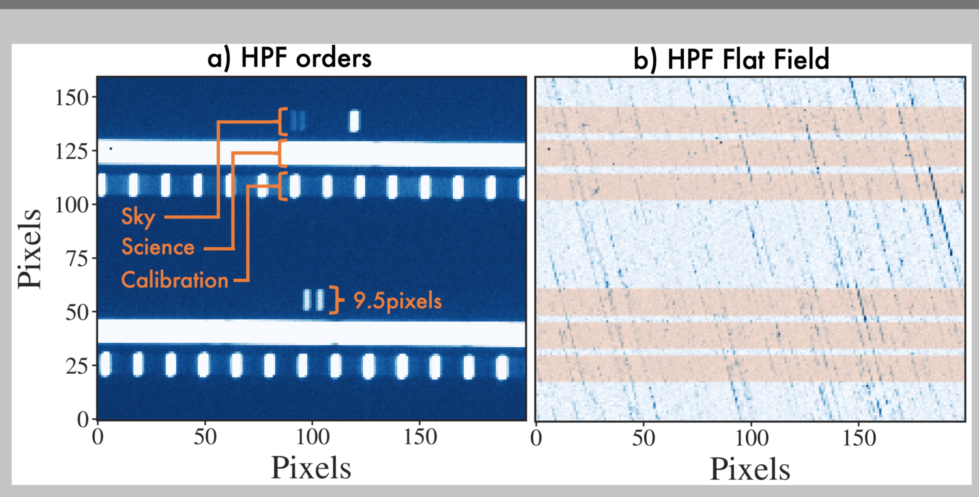

Figure 4: HPF's fiber slits overlayed on the crosshatch patterns

1D formalism for correction

- The vertical rectangular fiber slit of HPF enables us to reduce the 2D intra-pixel inhomogeneity into a simpler 1D problem.
- The cross dispersion profile of the HPF's trace is a well defined shape since the flux contamination from nearby wavelengths is constant across the profile. Let's denote this cross dispersion profile as a vector P.
- Let f be the scalar quantity which represents the total flux at any given column. Then the profile at that location is given by the vector fP.
- Let vector G be the effective gain*QE correction at each pixel inside the profile. Due to intra-pixel QE variation, G will be a function of the flux distribution inside each pixel.
- The sum extracted flux after proper flat correction at a given column is given by the dot product $G \cdot fP = f(G \cdot P)$.
- This separability of f and $G \cdot P$ at each column in a trace of HPF enables us to estimate $G \cdot P$ as a function of the flux distribution inside the column. The vertical alignment of the rectangular slit also guarantees same flux distribution across all the vertical 9.5 pixels.

Correction Algorithm

- The averaging of any sharp changes in the intra-pixel QE across the 9.5 pixels reduces the error in modelling of $G \cdot P$ with lower order polynomial.
- We first measure $\frac{G \cdot P(slope)}{G \cdot P(0)}$ for each extracted 1D pixel as a polynomial function of the *slope* of the spectrum at that pixel.
- Initial flat correction is done on the extracted spectrum using $G \cdot P(0)$ measured using a flat continuum source.
- Slope at each pixel is then estimated from the spectrum and the correction $\frac{G \cdot P(slope)}{G \cdot P(0)}$ is applied as a second step of flat correction.

Using Laser Frequency Comb for measuring intra-pixel QE

- For modelling $G \cdot P(slope)$, we need to measure the gain at maximum range of slopes. A sub-pixel tuneable Laser Frequency Comb (LFC) enables us to scan the sharpest instrumental profile across a pixel and estimate the intra-pixel QE variation.
- Currently our LFC enables us to only scan one pixel. Figure below shows the super-resolution trace of the instrumental profile generated by scanning the LFC at sub-pixel positions. Figure on the right, shows a simulation of the normalised profile trace for a simulated intra-pixel QE variation. To characterize every pixel using this method, we need to upgrade the current capabilities of the HPF's LFC.

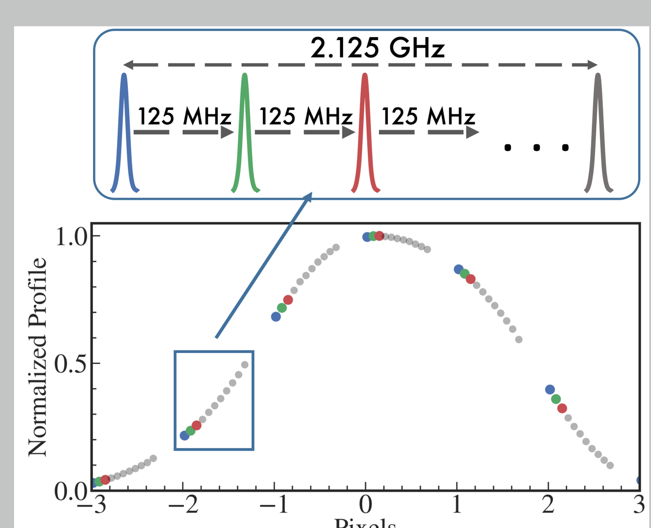

Figure 5: Super-resolution instrumental profile traced by scanning of LFC.

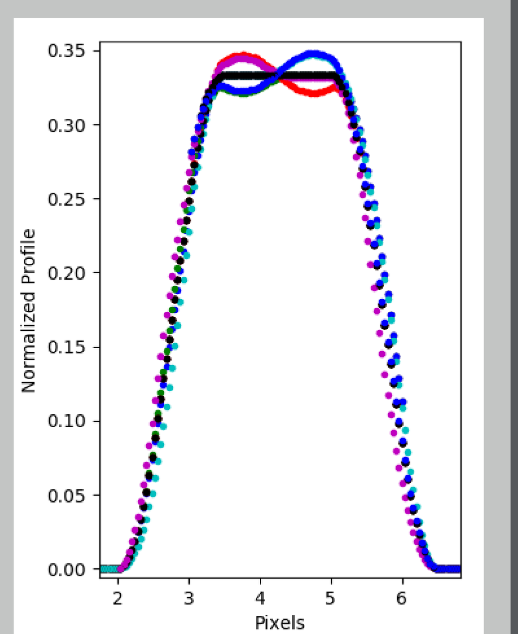

Figure 6: Simulated LFC profile traced by pixels with intra-pixel QE, during a full profile scan of LFC

Conclusion and Ongoing Work

- Our measurements show HPF's H2RG contains intra-pixel QE defects of $\sim$ **5**μm width. QE inside the defect is typically $\sim$ **54%**.
- We have outlined our proposed correction algorithm and measurements in this poster.

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