The algorithms behind the HPF and NEID pipeline

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Abstract. HPF and NEID are new high-resolution stabilized echelle spectrometers at the forefront of using radial velocity techniques to search for terrestrial mass exoplanets. Nightly data taken at the telescopes with large format detectors must be automatically processed into radial velocities in less than 24 hours. This requires a large investment in computer power and memory along with an automated pipeline that can check the quality of the data and handle issues without the need for human intervention. I will present an overview of our pipeline and discuss the, sometimes novel, algorithms and techniques we use to turn the unprocessed 2D echellograms into optimally extracted 1D spectra. These algorithms include the use of polygon clipping to rectify the curvature found in the beams on the detectors, the ability to fully account for aliasing in under-sampled data on the detector using flat lamp spectra, and the use of pixel count histograms to automatically match similar exposures and check the quality of the data. I will also discuss how our pipeline is built up from many independent modules, making it robust against failure and allowing it to be easily modifiable.

1. Introduction

The Habitable-zone Planet Finder (HPF) and the NN-explore Exoplanet Investigations with Doppler Spectroscopy (NEID) are new mechanically and thermally stabilized high-resolution echelle spectrometers designed to search for terrestrial mass exoplanets with precision measurements of host star radial velocities. HPF is a near-IR spectrometer on the 10 m Hobby-Eberly Telescope at McDonald Observatory, with a wavelength coverage ranging from $0.81 \rightarrow 1.28\ \mu$m, a resolution of $R \sim 55000$, and a photon limited radial velocity precision goal of ~ 1.0 m s^{-1} (Mahadevan et al. 2012, 2014). NEID is an optical spectrometer that will soon be installed on the 3.5 m WIYN Telescope at Kitt Peak National Observatory with a wavelength range of $0.35 \rightarrow 1.11\ \mu$m, a resolution of $R \sim 100000$, and a radial velocity precision goal of ~ 10 cm s^{-1} (Schwab et al. 2016). Both spectrometers reside in temperature controlled rooms beneath each telescope and are fed by three optical fibers: one fiber carries light from science target, another is offset onto the sky, and a third fiber carries light from the laser frequency comb (LFC) for accurate wavelength calibration. The combination of each spectrometer's mechanical stability, solid wavelength calibration, large wavelength coverage, high spectral resolution, and careful treatment of the data processing combine to achieve such high radial velocity precision.

High precision measurements require a careful consideration of the algorithms used in the data reduction and analysis pipeline such that we avoid introducing unwanted smoothing, information loss, algorithmic noise, or systematic shifts in our results. In this conference proceeding, we will discuss several of the algorithms that we have chosen to use in the HPF and NEID pipelines, focusing on the extraction of the dispersed beams on the detector into fully calibrated 1D spectra made ready for RV measurements.

2. Rectifying the Beams With Polygon Clipping

Detector pixels are quantized and follow a regular 2D grid. The dispersed beams from the fibers falling on the detector follow a curved path across the detector not in angular alignment with the regularly gridded pixels. This introduces two problems when trying to extract 1D spectra, the cross-dispersion direction is not necessarily in angular alignment with the detector pixels, and the location of the cross-dispersion aperture used to extract the beam follows a similarly curved path. Not taking these effects into account can lead to degradation in spectral resolution and introduce quantization into the localization of the extraction aperture. This quantization can lead to unwanted variation in the amount of background light inside the aperture or lost list in the beam wings at the aperture edges. This is important to consider if there is scattered background light or if beams are close enough on the detector that there is small amounts of cross-talk contamination between them. One solution is to forward model the spectrum and find the best fit model to the beams on the detector (Bolton & Schlegel 2010). Another solution is to rectify, or straighten, the curved beams before proceeding with the 1D extraction.

Traditional methods of rectification such as using linear or polynomial interpolation introduce unwanted smoothing, information loss, and algorithmic noise into the spectrum. More advanced methods such as sinc interpolation which try to reconstruct a continuous spectrum from the regularly sampled pixels can introduce aliasing artifacts for spectra that are under-sampled in the dispersion or cross-dispersion directions.

We have chosen the technique of polygon clipping for rectifying the beams, which is a flux conserving algorithm that essentially performs linear interpolation in 2D instead of 1D. Polygon clipping is commonly used in applications such as computer graphics, but is not commonly used for processing astronomical data. We adopt a variation of the technique outlined in Smith et al. (2007). The detector pixels are treated as square shaped polygons. Polygons representing pixels in the rectified reference frame are transformed into the detector reference frame and mapped over the polygons representing the detector pixels. The Sutherland & Hodgman (1974) method of polygon clipping is used to calculate the areas of each detector pixel that overlaps each pixel in the rectified reference frame. The flux in each rectified pixel is the sum of the fluxes of the overlapping detector pixels scaled by their areas of overlap.

3. Fixing the Problem of Under-sampled Beam Edges

HPF and NEID are spectrometers designed for exceptional optical quality. Illumination variations on the fiber ends due to guiding and pupil changes during an observation introduce unwanted RV shifts. To avoid this problem, the spot size on the HPF and NEID detectors are less than a single pixel, but a trade off of choosing to make the spot size so small is that the beam edges are under-sampled. The Nyquist theorem states that signal reconstruction requires sampling a signal at a rate that is at least twice as high as the highest frequency in the signal. The curvature of the beams across the regularly gridded detector pixels combine with the under-sampled beam edges to introduce aliasing.

4. Pipeline Automation

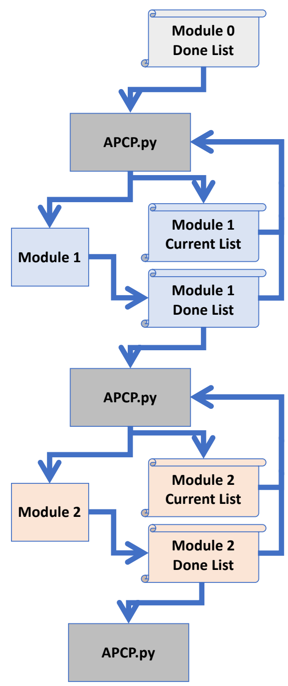

Figure 1. Caption goes here.

Acknowledgments. Acknowledgements go here.

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