The Design and Development of the NIRSPEC Data Reduction Pipeline for the Keck Observatory Archive

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Abstract. The Keck Observatory Archive, a collaboration between the NASA Exoplanet Science Institute and the W. M. Keck Observatory, serves science and calibration data for all current and retired instruments from the twin Keck Telescopes. In addition to the raw data, we publicly serve quick-look, reduced data products for four instruments (HIRES, LWS, NIRC2 and OSIRIS), so that KOA users can easily assess the quality and scientific content of the data. In this paper we present the design and implementation of the NIRSPEC data reduction pipeline (DRP) for KOA. We will discuss the publicly available reduction packages for NIRSPEC, the challenges encountered when designing this fully automated DRP and the algorithm used to determine wavelength calibration from sky lines. The reduced data products from the NIRSPEC DRP are expected to be available in KOA by mid-2016.

1. Introduction

The Keck Observatory Archive[1] (KOA, Berriman et al. 2014) archives data from all eight active and two inactive instruments on the twin W. M. Keck Telescopes in Hawaii. These instruments cover wavelengths from the optical to the infrared and produce data sets such as images and single object, multi-object and integral field spectra. KOA serves raw science and calibration data for all instruments and, when possible, matches science data to the calibration files needed for off-line data reduction.

The scientific quality of raw astronomical data is often difficult to assess. For example, at wavelengths longer than $\sim 1\mu m$ the radiation from the sky can be bright compared to the stars and galaxies that are of interest to archive users. Likewise, to the untrained eye, a raw spectrum provides almost no insight into the nature of an observation because it contains artifacts from the sky and has no wavelength information. Therefore, it is highly desirable to provide users with a product from which they can

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[1]`https://nexsci.caltech.edu/archives/koa`

quickly determine the science content. To accomplish this, an automated data reduction pipeline (DRP) is needed to calibrate the images to a level where the data content is easily descernible.

KOA currently employs DRPs for four instruments (HIRES, LWS, NIRC2 and OSIRIS) that produce browse quality data sets in addition to the raw data. In this paper we discuss the design and development of the DRP for the near-infrared echelle spectrograph (NIRSPEC).

2. The NIRSPEC Instrument

NIRSPEC (McLean et al. 1998) achieved first light on the Keck II telescope on April 25, 1999. It is an all-reflective, near-infrared, high-resolution spectrograph and is designed to operate over the wavelength region 0.95 to 5.4μm. A cross-dispersed echelle grating is used to obtain this wavelength coverage at high spectral resolution. A low dispersion mode is also available. Figure 1 shows example spectra from both dispersion modes. NIRSPEC is a vacuum-cryogenic instrument operating at a termperature of about 60K. Although not optimized for adaptive optics (AO), NIRSPEC can be located behind the AO System.

NIRSPEC has two detectors, a spectrographic indium antimonide (InSb) detector with 1024x1024 pixels and a slit-viewing mercury-cadmium-telluride (HgCdTe) infrared array with 256x256 pixels and a cutoff wavelength of 2.5μm.
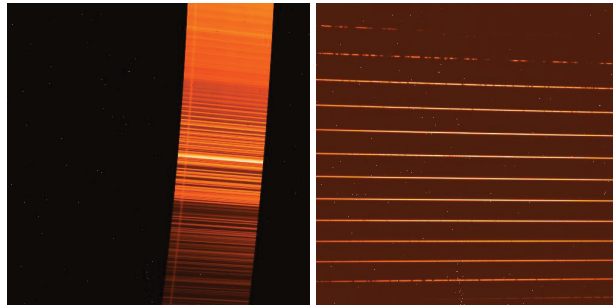

Figure 1.   *Left:* Low dispersion spectrum. *Right:* High dispersion spectrum.

3. Available Reduction Packages for NIRSPEC

There are a few DRPs available to reduce NIRSPEC data:

- The **REDSPEC** package is comprised of a set of IDL procedures. Its primary goal is the rectification of array data in which both spatial and spectral corrections are applied. It provides a basic spectral extraction which yields a text file containing wavelength and intensity.

- The **WMKONSPEC** package is a suite of IRAF tasks related to the reduction of low-dispersion spectra.

- The **Kelsonware** package is written in Python and is one of the more complicated packages to use.

All three of these DRPs rely heavily on user interaction during the extraction process. Although it is desirable to re-use packages that are already available, the archiving of Keck data is a fully automated process and thus this interaction is not desirable. Therefore, the KOA team started work on a new automated NIRSPEC DRP.

4. The NIRSPEC DRP

The NIRSPEC DRP is designed primarily for radial velocity searches and therefore is focused on the high dispersion mode of the instrument. It is a fully automated package, written in Python and is intended to create a quick-look browse product for KOA users.
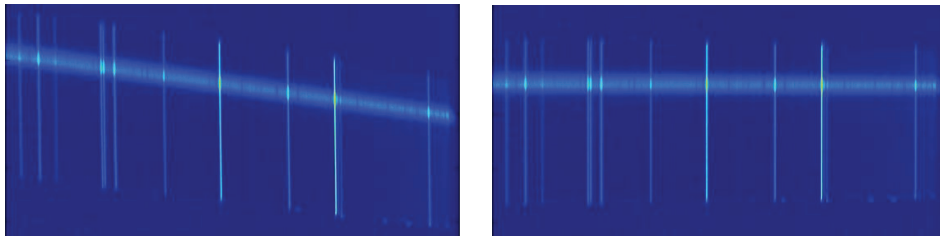

Figure 2. *Left:* Order cut from image *Right:* Spatial and spectral rectification applied.

The DRP is designed to process all object frames taken on any given night of observing. KOA utilizes a calibration association algorithm to find the dark and flat frames required for the reduction process. The calibration association is performed during the level 0 (raw) data processing and a new keyword (IMAGETYP) is added to each FITS header specifying the type of observation. The DRP uses this keyword along with the instrument configuration keywords to determine which calibrations to use for the object frame. The DRP then processes the data using the following steps:

- *Remove the instrument signature*: The median combined flat and dark frames are used to remove the instrument signature.

- *Locate each order*: Using the median flat frame, locate each order for the spectrum. The grating equation is used to estiamte the order location.

$$\lambda(c, \theta, \phi, M) = \frac{k_1 \sin(\theta) + k_2(\frac{w}{2} - c)\cos(\phi)}{M}$$

  where θ is the echelle angle, ϕ is the cross disperser angle, M is the order number, w is the width of the detector in pixels along the dispersion axis and k_1 and k_2 are constants that are determined emperically. The flat image is then used to find the lower and upper bounds of the order. These order traces are used to extract the object spectrum.

- *Rectify the orders*: Using spline interpolation, rectify the orders in both the spatial and spectral dimensions (Figure 2).

- *Extraction*: Extract the continuum, sky and noise spectra.

- *Determine wavelength solution from sky lines*: Wavelength calibration is done using known OH emission line wavelengths and relative intensities. A two-dimensional polynomial fit is used for wavelength calibration:

$$\lambda(c, M) = r_0 + r_1c + r_2c^2 + r_3M^{-1} + r_4cM^{-1} + r_5c^2M^{-1}$$

where c is the column pixel, M is the spectral order and the coefficients $r_0...r_5$ are determined by the method of least squares. This wavelength solution is then applied to all spectral orders.

- *Calculate signal-to-noise*: There are three source of noise that are taken into account - shot noise, read noise (RN) and dark current noise (DC). The total noise in a given pixel is determined by

$$\sigma_T^2 = \frac{(\sigma_{photon}^2 + \sigma_{RN}^2 + \sigma_{DC}^2)}{flat^2}$$

where

$$\sigma_{photon}^2 = \frac{R}{G} \qquad \sigma_{RN}^2 = (\frac{RN}{G})^2\frac{1}{n} \qquad \sigma_{DC}^2 = \frac{DC}{G}t$$

R is the pixel value in data numbers (DN), G is the gain ($5.8e^-/DN$), RN is the read noise ($23e^-/pixel$), n is the number of reads, DC is the dark current ($0.8e^-/sec/pixel$) and t is the exposure time in seconds. $flat^2$ is the value fo the corresponding pixel in the normalized flat frame.

The DRP produces several data products, including FITS and ASCII tables and a number of FITS images. Figure 3 shows some example data products.
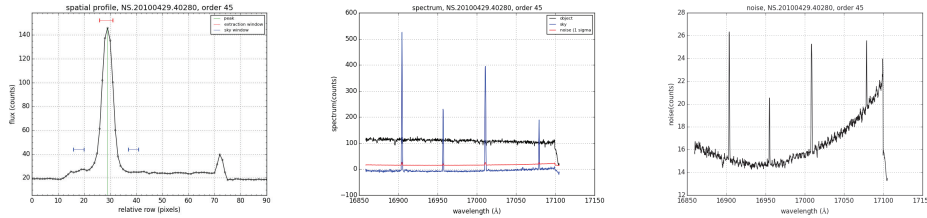

Figure 3. *Left:* Spatial profile fit *Center:* Flux, sky and noise spectra. *Right:* Noise spectrum.

References

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McLean, I. S., et al. 1998, in Infrared Astronomical Instrumentation, edited by A. M. Fowler, vol. 3354 of Proc. SPIE, 566