**Keck – HIRES Precise Radial Velocity Data Reduction Pipeline**

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**Observation Setup:**

Correct running of the Doppler pipeline requires careful setup of the HIRES spectrometer such that an array of Thorium-Argon lines falls on specified pixels. This setup causes in the iodine absorption lines, from the iodine cell, to fall on roughly the same pixels during each observing night. This precise setup allows the downstream data analysis to proceed with the highest precision possible.

**Calculation of the Barycentric Correction:**

During observations, the HIRES exposure meter must be used in order to precisely determine the mid-point time of the observation. The exposure meter ensures an accurate measurement of the flux weighted mid-point time, even in variable observing conditions. The flux-weighted mid-point time of the observation is then used to calculate the barycentric velocity. This barycentric correction is subtracted from each RV measurement to ensure all measurements are in the rest frame of the observatory.

Calculation of the Flux weighted mid-point time

The HIRES instrument includes a device capable of measuring, in real time, the flux as a function of time, during each on sky exposure. The flux weighted midpoint time is collected in the header of each spectrum as EXM0FWMP.

The flux weighted mid point is recored as the number of seconds after the exposure begins. This value is converted into a clock time by mtfits.pro. This value is finally recorded in the barycentric correction log as BJD.

**Raw Reduction:**

These routines produce a 1D spectrum from the 2D spectrogram that is created upon readout after the observation. In this process the bias is subtracted, the pixel array is flat field corrected, the inter-order light or sky background (depending on the decker used) is subtracted, and each spectral order is collapsed in the spatial direction producing a spectrum with flux as function of wavelength. The wavelength values as a function of pixel should be within plus or minus one pixel of their historical positions, so long as the HIRES setup is performed correctly.

**Commonly Used terms:**

PSF: Point spread function (PSF) aka line spread function. This a measurement of the shape of a spectral feature, either stellar or from a calibration source.

B-star: A term used for rapidly rotating stars, of spectral type A or B. Since stars of this nature have few spectral features, they act as ‘calibration lamps in the sky’. They are especially useful for determining the PSF in template creation. This article summarizes the high quality and low quality stars that fit this category:

http://iopscience.iop.org/article/10.3847/2515-5172/aab7e9/meta

FTS Iodine: Fourier Transform Spectrum of the iodine cell. There is a single FTS iodine spectrum that is used in all parts of the Doppler Code. It was created using the iodine cell that is currently in use inside HIRES.

Chunk: Within the Doppler code the spectrum is divided into 718 pieces, each two-Angstroms long. The majority (though not all) of the Doppler code operates on a single chunk at a time.

Run\_number: This have run from j01 to j299. Consecutive nights have traditionally been treated as the same run. This is not required. The prefix: ‘rj’ is sometimes found in the code as required. There are currently 15 mentions in the code. All reduced spectra have a run number. This is typically repeated in the output files produced by the doppler code.

Tag: This is completely arbitrary, and is assigned upon running of the code. Only files output from the doppler code will have this code.

cf\_starname: This is an auxilliary file that is created that holds the observation information. This file is reference internally by the doppler code, but no critical information is stored.

Example file: ‘cf’+starname+’\_’+tag+’.dat’.

eg: cfk01439\_ad.dat

VD:

VDIOD:

DSST:

Vanking?:

VST:

**Star naming conventions:**

Traditionally stars have numbers with no prefix. These are assumed to be ‘HD’ stars. Cataloging of stars is default ‘HD’, however other starnames are ok, so long as they have a lettered prefix: ie: ‘HIP’, ‘GL’, or ‘KIC’.

We use stars that begin with the prefix ‘HR’ as calibrators. These are *always* stars of spectral type O, A or B. Commonly they are referred to as ‘Bstars’ in the code. The naming convention is such that any starname beginning with ‘HR’ is assumed to be a Bstar.

Observation Number: A typical observation number is rj211.78. This is established by the run number (ie: j01 – j299), prefixed with an ‘r’ once the raw image (2D echellogram) has been passed through the raw reduction and a 1D Spectrum(with intensity as a function of pixel number) has been produced. The number after the ‘.’ is determined by the number of the observation for the given run number. For example: ‘r’+run\_number+’.’+observation\_number.

**Coordinate Database**

The coordinates of the target observed are required in order to correctly calculate the barycentric correction. The Doppler code uses a hierarchical list of catalogs that hold coordinates. The right ascension, declination, RA-proper motion, DEC-proper motion, epoch, and if available distance are used in the barycentric correction. It is possible to simplify this such that only a single file is queried (kother.ascii).

**Logsheet structure:**

Example file: `nexsci\_dopcode/raw\_reduction/logs/j150.logsheet1\_part`

Each logsheet contains a header and a body. The header contains dates of observation, observers, and instrument settings. The body holds one line per observation. Both calibrations and stars are logged, one per line. The body serves as the input to the barycentric correction.

Logsheet body details:

Column 1: Observation number: sequential. Starting point non-critical

Column 2: Object Name

Column 3: ‘y’ or ‘n’. Is iodine in the lightpath?

Column 4: Flux weighted mid-point time. (UT format)

Column 5: Exposure time in seconds

Column 6: Geometric midpoint time (UT format). Non-critical

Columns 7 Decker Name (non-critical)

Columns 8 Exposure meter reading (non-critical)

Columns 9-n All subsequent columns are optional aka non-critical.

Structure of kbcvel.ascii File  
Column 1: Observation Name

Column 2: Starname

Column 3: Barycentric Correction (m/s)

Column 4: BJD – 2.44e6

Column 5: Hour Angle (non-critical)

Column 6: Observation type: Iodine? Non-iodine? Calibrator?

**Doppler Code Modules:**

Required Top Level IDL Routines:

The following routines must be sequentially, in the order listed below, in order to produce radial velocities. All spectra collected from HIRES are saved in a format called RDSK. This is similar to fits format, with a header and data array.

**make\_vdiod.pro**

Purpose: Creates VDIOD files, which are used in PSF determination and de-convolution of the stellar template observation. Run time: 2 minutes per observation.

Inputs:

1) A stellar spectra of rapidly rotating, hot, stars (we call the B stars, although they can be A or B spectral type. Since rapidly rotating stars have few spectral features, this routine examines only the iodine absorption features. The rapidly rotating star mimics a continuum spectrum calibration lamp, with the benefit of also passing through all of the telescope optics (which calibration lamps do not).

2) The FTS Iodine spectrum is in binary format. This file holds the position and intensity of the iodine absorption features as a function of wavelength. In use, each spectral feature in the FTS iodine spectrum is convolved with the PSF to best match the observed B-star spectrum taken through iodine.

Output:

IDL save file prefixed with VDIOD. The file contains the point-spread function of each chunk of iodine spectrum without any information about wavelength zero point or radial velocity.

File name format: vdiod7565\_rj270.283.ad

‘vdiod’+Bstar\_name+’\_r’+run\_number+’.’+obs\_number\_’.’+tag

Bstar\_name is the ‘HR’ name of the star, without the prefix ‘HR’. In the above example the B-star observed was HR7565. The run number can be anything. It is customary to use a single letter followed by 3 letters. The tag also consists of a sequence of letters (typically 2-3).

Example calling syntax:

IDL> make\_vdiod, ‘k01439’,’aa’

If necessary, this program is called from make\_dsst.pro

**make\_dsst.pro**

Purpose: Creates a de-convolved stellar template (DSST). The spectrum is broken down into chunks, each holding a section of spectrum that has been de-convolved by the PSF. DSST chunks are slightly larger than the chunks in VD files (2 Angstroms) to allow for Doppler shifts due to changes in the barycentric velocity relative to the target star at the time of observation. Run time: 1-3 hours.

Inputs:

Target star spectrum without iodine.

FTS iodine spectrum.

VDIOD files, typically 3-6 of them, derived from B-stars (see makevdiod.pro) observed adjacent to the iodine free target star spectrum.

Outputs:

IDL Save File containing the de-convolved stellar template, broken into chunks of spectrum of approximately 3 Angstroms.

File name format: dsstk01439ad\_rj174.dat

‘dsst’+ starname + tag +’\_r’ + run\_number + ‘.dat’

Example calling syntax:

IDL> make\_dsst,’k01439’,’aa’,run\_tag,vdtag=’aa’

Where the run\_tag is the rj174, from the example above.

**dop\_driver.pro**

Purpose: Creates a velocity data structure structure for each observation of a given star (VD files), which stores the PSF, wavelength zero-point and radial velocity information for each chunk of a single target star spectrum. Run time: 2-6 minutes per stellar observation.

Inputs:

Set of target star spectra with iodine.

FTS Iodine spectrum.

De-convolved stellar spectrum of the same target star.

Outputs:

Velocity data structure, one per target star observation. These are called VD’s, as it holds each stars velocity data. This file holds PSF, wavelength zero point, and radial velocity information for each individual two Angstrom chunk of the spectrum.

File name format: vdadk01439\_rj172.714.

‘vd’+ tag + starname + ‘\_r’ + run\_number + ‘.’ + observation number

Example calling syntax:

IDL> dop\_driver, ‘rj174.496’,’aa’,vdtag=’aa’

**jjvank.pro**

Purpose: Creates the final data product (VST file), which is a radial velocity measurement for each target star spectrum with associated errors, fit parameters, and SNR values. In this process, the VD files are analyzed as a group and the radial velocity measurements of the individual chunks are weighted based on performance of each chunk across all of the spectra for that star. The best performing chunks are given the highest weight. The chunks that show low precision are given lower weights.

Inputs:

All VD files for a single star.

Output:

An IDL save file that holds the RVs, RV errors, chi-squared and SNR for each target star spectrum taken with iodine results from this program. This could easily be converted to a csv file for convenience.

File Name format: ‘vst’ + starname + ‘.dat’

Example calling syntax:

IDL> jjvank,starname,tag\_name

jjvank,’k01439’,’aa’

**Required Input Files:**  
Static files: Fourier Transform Spectrum of the iodine cell.

User provided spectra:

1) An iodine free spectrum of the target star (template).

2) Rapidly rotating stars observed near in time and nearby in position on the sky to the target star iodine-free spectrum.

3) Target star observations with iodine (minimum 3).

Consider the example star named K01439. Listed below is a log of the observations required for calculation of six precise radial velocities. This log file must have the same six columns as shown, and be named as environmental variable DOP\_BARYFILE. The line numbers are included only for clarify and should be omitted in practice.

Lines 1-6: Observations of the target star, with iodine in the light path.

Line 10: The iodine free (aka template) observation of the target star.

Lines 7-9, 11-13: Observations of rapidly rotating stars, observed immediately before and immediately after the template observation of the target star. The same star can be observed before and after the template or two different stars can be used. The rapidly rotating stars should be near in the sky and at similar air mass to the template star observation. Since they are bright stars, all of them have HR numbers. HR numbers are *only* used for rapidly rotating stars.

--------------------------------------------------------------------------

Filename Star BCVel(m/s) BJD-2.444e6 HrAng. Obtype(t/o)\*

--------------------------------------------------------------------------

1 rj172.714 K01439 5677.444 16474.877683 -2.095 o

2 rj173.974 K01439 3686.374 16487.779798 -3.601 o

3 rj173.1181 K01439 3407.480 16488.849081 -1.868 o

4 rj178.105 K01439 -1990.850 16518.836750 -0.195 o

5 rj180.485 K01439 -4226.230 16531.812019 0.067 o

6 rj211.78 K01439 -4960.389 17265.033970 5.575 o

7 rj174.496 HR7543 0.000 16495.063403 0.000 o

8 rj174.497 HR7543 0.000 16495.064155 0.000 o

9 rj174.498 HR7543 0.000 16495.064896 0.000 o

10 rj174.499 K01439 1946.916 16495.083987 4.178 t

11 rj174.504 HR7457 0.000 16495.105174 0.000 o

12 rj174.505 HR7457 0.000 16495.105995 0.000 o

13 rj174.506 HR7457 0.000 16495.106863 0.000 o

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\* t = template(no iodine), o = observation (with iodine)

**Output files:**

Lines 1-6 produce VD files.

Line 10 produces a de-convolved stellar template (DSST)

Lines 7-9 and 11-13 produce VDIOD files.

A VST file (velocity structure) is also produced but does correspond to any specific observation. It holds radial velocity measurements, one for every spectrum of the target star observed with iodine. The output files for the lines 1-13 above have the tag number ‘ad’. Run numbers vary from j172 to j211.

1 vdadk01439\_rj172.714

2 vdadk01439\_rj173.974

3 vdadk01439\_rj178.105

4 vdadk01439\_rj178.105

5 vdadk01439\_rj180.485

6 vdadk01439\_rj211.78

7 vdiod7543\_rj174.496.ad

8 vdiod7543\_rj174.497.ad

9 vdiod7543\_rj174.498.ad

10 dsstk01439ad\_rj174.dat

11 vdiod7457\_rj174.504.ad

12 vdiod7457\_rj174.505.ad

13 vdiod7457\_rj174.506.ad

**Environmental variables:**

Control of Paths: All programs should be in IDL\_PATH\_DOP, all other files in IDL\_PATH\_DOP\_BASE

IDL\_PATH\_DOP: must include primary dopcode direcotry and sub-directories: pros/, and markwardt/

IDL\_PATH\_DOP\_BASE: Parent folder that contains primary dopcode directory

Static files outside of IDL\_PATH\_DOP:

DOP\_I2\_ATLAS\_PATH: # Full path to iodine atlas

DOP\_I2\_ATLAS="ftskeck50.bin" # Name of FTS iodine. Relative path.

DOP\_BARYFILE="kbcvel.ascii" # full path and name of kbcvel.ascii log file

DOP\_DSST\_OVERRIDE="dsst\_override.txt" # full path and name to override file. (optional)

Used to store the DSST template name when default name is not used.

DOP\_NSO\_ATLAS="nso.bin" # Full path and name of NSO solar atlas.

DOP\_IPGUESS\_K2="/home/doppler/dopcode/ipguess\_k2.dat"

# Full path and name to initial guess file.

DOP\_VD\_EXAMPLE="/mir3/files/vdiod3314\_rj13.2275.j" # Full path and name.

# Structure of this file is used to crate new files.

DOP\_KECK\_STRUC="/mir3/keck\_st.dat" # IDL Structure containing starnames and B-V values.

DOP\_JJHIP="/home/doppler/dopcode/jjhip\_v2.dat" # IDL Structure containing starnames and B-V values.

Directory structure for input/output files.

DOP\_PLANETS\_DIR # planets holds the cf structures and temporary velocity structures.

DOP\_FILES\_DIR # Most newly created files are output here.

DOP\_RV\_OUTDIR # Radial Velocity Structure stored here.

DOP\_SPEC\_DIR # Input spectra stored here.

DOP\_SPEC\_DB\_DIR # Alternate type spectra stored here.

Lack of these files is non-critical to the code.

DOP\_RK\_VEL\_DIR="/mir3/rk\_vel/" # pre-upgrade RVs stored here.

This will not be needed for new users.

Lack of these files is non-critical to the code.

DOP\_DIR # Location of primary routines used in doppler code.

Raw Reduction Environment Variables

RAW\_RAW="/mir3/raw/" # Location of raw files.

RAW\_ALL\_OUT\_FITS="/mir3/iodfits/" # Output directory of .fits files

RAW\_ALL\_OUT\_FITS\_DB="/mir3/iodfitsdb/" # Output directory of deblazed .fits files

RAW\_MID # Location of middle chip raw reduction routines.

RAW\_MID\_OUT # Output directory of middle chip spectra (rdsk format)

RAW\_RED # Location of red chip raw reduction routines.

RAW\_RED\_OUT # Output directory of red chip spectra (rdsk format)

RAW\_BLU # Location of blue chip raw reduction routines.

RAW\_BLU\_OUT # Output directory of blue chip spectra (rdsk format)

RAW\_HAMRED\_BOTTOM # Location of j\_bottom.txt file. Part of Hamred reduction file.

MIR3\_LOG # Directory holding logsheets.

MIR3\_BARY # Directory holding barycentric corrections log.

**13 Dec 2017 Updates to the code**

**38 .dat files (6 are needed or potentially needed)**

bstar\_all\_pars\_c2\_b5\_jan2015.dat - essential

bstars\_obnm.dat obsolete

bstars\_obnm\_prek.dat obsolete

dsst\_k00157\_nso\_test.dat obsolete

example\_info.dat obsolete

example\_stitch.dat obsolete

idlsave.dat temp file (non-critical)

-This is the default for IDL save files.

info.dat obsolete

iodine\_p4\_pnnl\_lo\_apod.dat obsolete (in th code but never used)

ipcf.dat obsolete. Mentioned in make\_ipguess.pro

Should be removed from code.

ipcf\_k2.dat obsolete. Mentioned in make\_ipguess.pro

Should be removed from code.

ipcf\_mag.dat obsolete. Mentioned in make\_ipguess.pro

Should be removed from code.

ipguess.dat Critical (requires further documentation)

ipguess\_k2\_2015.dat Potentially needed (requires further investigation)

ipguess\_k2.dat Likely critical (requires further investigation)

ipguess\_quad.dat Likely obsolete

ipguess\_quad\_k2.dat Likely obsolete

jjhip\_v2.dat Currently required, but could be removed.

Only B-V values are used.

keck\_bwav.dat obsolete

keck\_iwav.dat obsolete

keck\_rwav.dat obsolete

library.dat obsolete

lick\_st.dat obsolete

median\_bstar\_b5\_c2\_pars.dat Critical

myinfo\_9407.dat obsolete

myinfo\_95735.dat obsolete

myinfo\_ab.dat obsolete

myinfo.dat obsolete

normalize\_bstar.dat obsolete

prekeck\_dsst\_template.dat obsolete

Sacred\_VD\_b5\_c2\_sep2014.dat obsolete

tellist\_k2.dat obsolete

test\_vd.dat obsolete

t\_resid.dat obsolete

vdiod\_obnms.dat obsolete

vd\_sub1.dat obsolete

vdtest\_keck.dat obsolete

vdtest\_lick.dat obsolete

vesta\_bc.dat obsolete

**3 \*.dsk files: all are obsolete:**

bstar\_j13.dsk tellist\_k2.dsk tellist\_valenti.dsk

**14 text files: dsst\_override.txt is the only required .txt file**

fm\_exmaple.txt obsolete

eta\_earth.txt obsolete

fm\_readme.txt obsolete

keck\_standards.txt obsolete

notes.txt obsolete

notes\_dsst.txt obsolete

rerun.txt obsolete

sim.txt obsolete

rvtell.txt obsolete

sub\_notes.txt obsolete

vel\_standards.txt obsolete

to\_revank\_june2016.txt obsolete

k2\_19\_dsst\_notes.txt obsolete

dsst\_override.txt required

4 \*include files are all obsolete.

4 \*sav files are all obsolete.

Programs that we maintain, but are not critical to running the code

Notes on how to identify the calibration files from the header:

So we have these different types of calibration files that we need to identify:  
  
- Focus  
- Iodine  
- ThAr  
- Wideflats  
- B stars  
- Order finder (just any B star observation during the night, but preferably the first science observation)  
  
Here is how I’m thinking we can identify these files based on header keywords:  
  
Common for all calibration files:  
 - exposure meter off, EXM0STA == “Safe/Off”  
 - lamp filter is ng3, LFILNAME == “ng3”  
  
- Focus:  
 - iodine out, IODIN == “F" and IODOUT == "T"  
 & pinhole decker, DECKNAME == “D5”  
 & thorium-argon lamp on, LAMPNAME contains “ThAr” (case-insensitive)  
  
- Iodine  
 - iodine cell is warm, TEMPIOD2 == 50±1  
 & iodine cell is in the light path, IODIN == “T" and IODOUT == “F”  
 & quartz lamp is on, LAMPNAME contains “quartz” (case-insensitive)  
  
- ThAr  
 - iodine cell is out of the light path, IODIN == “F" and IODOUT == “T”  
 & thorium-argon lamp is on, LAMPNAME contains “ThAr” (case-insensitive)  
 & decker is not pinhole, DECKNAME != “D5”  
  
- Wideflats  
 - iodine cell is out of the light path, IODIN == “F" and IODOUT == “T”  
 & decker is C1, DECKNAME == “C1”  
 & must have at least 5(?) of these files to operate   
  
- B star  
 - iodine cell is warm, TEMPIOD2 == 50±1  
 & iodine cell is in the light path, IODIN == “T" and IODOUT == “F”  
 & exposure meter on, EXM0STA == “Ready”  
 & target name starts with “HR”, TARGNAME.startswith(“hr”) (case-insensitive)  
 & SNR > 100, EXM0LSUM >= 125k