REDSPEC Data Reduction Manual

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1 Introduction

The following sections provide an introduction to spectroscopic reduction methods for new users, and important background information for NIRSPEC users in particular.

1.1 Data Reduction Strategies

The flux incident on the Earth's atmosphere from an astronomical source is affected by several factors before it becomes a detected signal in an instrument. These factors include:

- wavelength and airmass dependent absorption by the atmosphere
- wavelength dependent transmission losses through optical components
- wavelength and position dependent response by the detector
- wavelength and time dependent background thermal and molecular emission
- position and time dependent dark current from the detector

Since the final signal on the detector pixel at (x,y) is the sum of the attenuated flux plus additive terms from background emission and dark current, the additive terms are generally removed first. A standard observing strategy is, for point-like sources, to record the spectrum of the target at two different positions along the spectrometer slit by nodding the telescope between exposures. Alternatively, for extended sources, the second observation can be made with the source completely off the slit so that only background is observed. If A and B refer to frames taken with the object at two different positions on the slit, or ON−OFF slit, then a subtraction $(A - B)$ of the two frames will eliminate any additive terms (such as dark current and sky background) at each pixel position provided they are not variable over the time scale of the measurements. Using an ABBA observing pattern is the most efficient approach for obtaining multiple pairs of data, since one telescope nod move is eliminated.

If a spectrometer produces images of the entrance slit that are dispersed uniformly onto the rows and columns of the detector with no distortions, then only a spectral rectification is required, in which the relationship between pixel number and wavelength is established. If the spectra are curved or distorted with respect to the detector rows, then a spatial rectification is also required. Spatial rectification with REDSPEC is accomplished by *summing* an $A+B$ pair of a (relatively bright) calibration star to produce an image with two spectra. On the basis of polynomial fits to each spectral trace, and the calculation of gaussian centroids to define their separation, the image is re-mapped to produce straight spectral traces with respect to the detector rows. Spectral rectification requires a polynomial fit to wavelengths of arc lamp lines, or OH night sky emission lines, as a function of pixel number. The application of these two steps results in a re-mapping of the the raw images onto a coordinate system with uniform intervals in spatial extent along the slit, and in wavelength along the dispersion axis. (For some applications, more sophisticated spatial mapping may be necessary.)

For an on-slit nod observation of a point source, the differenced image, $A-B$, will contain two independent spectra (one positive, one negative) of the target object. Both spectra will be distorted by wavelength dependent absorption in the atmosphere and instrument. To remove these effects requires separate observations of a source with a featureless spectrum —— a calibration star. For low resolution observations, late F stars provide spectra with weak narrow lines that are not resolved. For higher resolution work it may be more useful to observe A stars with very few intrinsic lines and interpolate over these known features. Dividing the target spectrum by this calibration star spectrum, observed at the same airmass, eliminates the telluric absorption and instrument transmission features. Multiplying this ratio by a normalized blackbody function with a temperature corresponding to the spectral type of the calibration star provides a relative flux calibration.

Two considerations must be taken into account when forming the spectral ratio of the target and calibration star: (1) If the instrument parameters (grating angles) have changed between the target and calibration star observations, then one spectrum will be shifted in wavelength with respect to the other. (2) It is likely that the target and calibrator star spectra will fall on different pixels, and therefore the ratio will contain the relative response of those pixels. The first effect is corrected by applying a spatial and spectral re-mapping or rectification to both the target and calibration star and dividing only the corresponding spectral region. The second effect is solved by illuminating the slit with a flat field source (obtained with the same instrumental setup) and dividing the $A-B$ target and $A-B$ calibration star difference frames each by the appropriate flat field to account for the variations in the pixel to pixel response.

Prior to dividing the flat field into these difference frames, a dark frame, which includes the bias, observed with the filter blanked off, should be subtracted from the flat field exposure to account for the positive offset resulting from these terms. The dark and flat exposures should have the same integration time. For the target and calibrator, the $A-B$ differencing eliminates these offsets.

Following the $A-B$ pair subtraction, flat-fielding, and rectification, the spectrum of the target can be extracted. REDPSEC provides tools to perform all of these functions, as well as checks on the quality of fits to the arc lamp or OH night sky lines, saturation warnings for flat fields, calibration star, and target frames, Fourier filtering to remove the effects of internal fringing, and bad pixel removal.

Although designed specifically for the NIRSPEC instrument at the Keck Observatory, REDSPEC has been used successfully to reduce spectra from many other instruments.

1.2 Background for NIRSPEC Users

NIRSPEC was designed as a crossed-dispersed high-resolution spectrometer with an emphasis on maximizing throughput to take full advantage of the collecting area of the Keck telescopes. An echelle grating with 23.29 lines/mm blazed at 63.5 degrees is cross-dispersed by another grating having 75.75 lines/mm and a blaze angle of 10 degrees. When the echelle grating is replaced by a flat mirror and a second set of slits orthogonal to the original set is used, a low resolution mode is obtained. When observing in echelle mode, the dispersion direction runs along the horizontal or x-axis on the screen. In the low-resolution (grating) mode, the dispersion runs vertically on the screen. To limit the crossing of quadrant boundaries of the detector, the low resolution spectrum is imaged on the two right hand quadrants of the detector. Two slit lengths, 12″ and 24″, are available in echelle mode; in grating (low resolution) mode, there is only a single, long slit of 42″.

One feature of NIRSPEC's design is that the echelle grating is used in the Quasi-Littrow mode (QLM) with an out-of-plane angle (γ) of 5 degrees. This approach to the design gives a much higher "on-blaze" efficiency for the grating than would be obtained at the same angle in the "near" Littrow mode, since the true Littrow condition cannot be obtained without the incoming and outgoing beams vignetting. The penalty for QLM is that the slit image on the detector is not perpendicular to the direction of the spectral dispersion, and the tilt is a function of wavelength. To further improve NIRSPEC's throughput, the final f/3 camera in the spectrometer is a silver-coated three-mirror anastigmat (TMA) with no central obstructions. While the TMA is effective in reducing aberrations it has the property that the focal length is different in the two orthogonal directions (along the dispersion and perpendicular to it). In other words, the plate scales are different along these two directions. Along the echelle dispersion direction the scale is 0.144 arcsec/pixel and along the cross-dispersion direction the scale is 0.193 arcsec/pixel. This spatial distortion effect is actually put to good use in the design by orienting the camera in such a way that the well-known anamorphic magnification of the echelle grating is largely canceled. The central wavelength (blaze wavelength) in each echelle order (m) is given by

$$\lambda m_{ech} = 76.56 \mu m$$

and for the cross-disperser by

$$\lambda m_{cdg} = 4.155 \mu m$$

A central wavelength of 0.957 μm occurs in order m_{ech}=80, whereas 5.47 μm occurs in order 14. The free spectral range in a given order is λ/m. Only for the shortest wavelengths is it possible to capture one free spectral range on the detector.

Order overlap in the cross-disperser is avoided by using a custom set of order sorting filters called NIRSPEC1, NIRSPEC2,... NIRSPEC7, KL, and M. Using the NIRSPEC ECHELLE FORMAT SIMULATOR (EFS), profiles of the filters may be plotted and the wavelength coverage at particular cross-disperser and echelle grating settings displayed (the IDL-based EFS software is available for download from the Keck website:
http://www2.keck.hawaii.edu:3636/realpublic/inst/nirspec/EFS.html).
Nominally, the resolving power in echelle mode, with the 3 pixel (0.″43) slit, is about 20,000

(15 km/s) and, in the low resolution mode, with the 2 pixel (0.″39) slit, is about 2,000 (150 km/s). Actual performance may be slightly worse than this because of a slight degradation in the focus which occurred when the detector was upgraded in September 2000; the true resolution can be determined from the width of unresolved arc lines.

The outcome of the NIRSPEC design, which maximizes the throughput across the large wavelength range from 0.95-5.5 μm, is that the spectral images on the 1024 $\times$ 1024 detector are spatially and spectrally distorted. Therefore, the image must be rectified spatially and spectrally to produce a product with a linear spatial scale along the slit length direction and uniform wavelength intervals along the dispersion direction. The IDL-based software modules described below were developed at UCLA to provide NIRSPEC users with the basic tools to make this rectification in both high- and low- resolution modes.

2 Introduction to REDSPEC

The REDSPEC code is comprised of a set of IDL procedures. The graphical user interface (GUI) is based on IDL widgets. The primary goal of REDSPEC is the rectification of array data in which both spatial and spectral corrections are applied. Two algorithms are provided for this, one based on interpolation and the other on pixel mapping. In the former, the intensity of each rectified pixel is determined by interpolating over the original image. In the latter, the intensity of an original pixel is distributed into several pixels in the rectified array in a linear fashion, such that the total intensity can be conserved. The difference between the results acheived using these two methods is on the oder of 1%. The interpolation algorithm is faster, and hence is used as the default. Post-rectification reduction depends on the specific user's data needs, but the REDSPEC code also provides basic spectral extraction, yielding an ASCII file containing wavelength and intensity.

The operation of REDSPEC involves the following steps:

- bad pixel removal (optional)
- spatial rectification (implicit)
- spectral line identification (implicit)
- dispersion solution for each order (implicit)
- sky subtraction (implicit, requires nod pair or on/off pair)
- division by flat field, i.e. flat−dark (optional)
- removal of telluric atmospheric absorption lines (optional)
- removal of fringing effects (optional)
- division by calibration star spectrum, scaled by normalized blackbody (optional)
- spectral extraction (implicit)
- plotting (optional)

Requirements for running REDSPEC:

1. IDL version 5.3 or higher
2. Access to the Astronomical Users Library (AUL) (see http://idlastro.gsfc.nasa.gov/ for free download). Note that at many institutions this library is in place and maintained by the system administrator.
3. An ASCII file comprised of arc lamp or OH night sky line wavelengths, corresponding to the observed spectral region. A basic list of arc lamp lines is included in the NIRSPEC EFS overlays menu. An excellent reference for precise OH night sky line wavelengths is Rousselot et al. (2000, A&A, 354, 1134).
4. IDL paths must point to directories containing the REDSPEC code and the AUL procedures.

This manual describes each step in the REDSPEC data reduction process and the available options in detail. It is written for the first time user with little or no experience in spectroscopic data reduction. The organization reflects the structure of REDSPEC. For setup (§§3.1 and 3.2), the PARFILE procedure is called to load a parameter file which specifies the paths to the data and calibration files. Three routines are then executed. The first, SPATMAP (§3.3), performs the spatial mapping, the second, SPECMAP (§3.4), performs the spectral-line mapping, and the third, REDSPEC (§3.5), rectifies all images, performs the algebraic operations on the image arrays, and carries out a first order spectral extraction. Alternatively, the data may be rectified and saved for spectral extraction by other means (§3.6). Co-addition of multiple observations is carried out after each pair extraction. Post-reduction processes, such as flux calibration and concatenation of adjacent spectral regions, are left to the user. A summary of the data reduction steps appears at the top of each section.

3 REDSPEC User's Manual

3.1 Getting Started

Section Summary

→ (1) Create data reduction subdirectory for each object/filter/echelle order
→ (2) CD to the appropriate subdirectory
→ (3) Use image of arc lamp spectrum and the NIRSEPC EFS and/or other references to create file spec1.in and spec2.in if necessary

Organization of data directories is important. These must be created *by the user* before launching IDL and starting REDSPEC. For each object observed in a particular NIRSPEC set up, *i.e.* filter, echelle position, etc., a corresponding directory must be created in order to store the products of REDSPEC. For data taken in echelle mode, separate subdirectories are needed for the results from *each order*; REDSPEC only reduces one order at a time. For example:

```
/data/1/user/reduced_2001/star1/order47

/data/1/user/reduced_2001/star2/order47

/data/1/user/reduced_2001/star2/order48
```

For low resolution mode, subdirectories should correspond to order-sorting filter or grating angle. For example:

```
/data/1/user/reduced_2001/star1/nirspec3

/data/1/user/reduced_2001/star2/nirspec3

/data/1/user/reduced_2001/star2/nirspec4
```

Move (cd) to the appropriate subdirectory, for example,
cd $/data/1/user/reduced\_2001/star1/order47$,
from which IDL will be launched and the REDSPEC procedures called. Data products from the reduction will be saved here. **Data product names are always the same** (see list in §3.6). Therefore, if reducing multiple pairs of data from the same object, either create another level of subdirectores, or else rename the product files after each reduction.

At least one spectral line list is required as input to run REDSPEC. A second file is optional. These files must be called spec1.in and spec2.in and contain the vacuum wavelengths in **microns** of the arc lamp or OH night sky lines in the spectral range of the data. For echelle mode data, spec1.in should contain the arc lamp or OH sky line wavelengths for the particular order being reduced. For low resolution mode data, spec1.in should contain the arc lamp or OH sky line wavelengths for the particular *filter* being used for the observation.

Reference arc lamp wavelengths are available in the overlays menu of the NIRSPEC EFS. Additional references for arc lamp and OH night sky line wavelengths are available from the NOAO website (http://www.noao.edu/kpno/phoenix/), from the NIST database (http://physics.nist.gov/cgi-bin/AtData/main_asd), and from the literature (see §2).

An example of the format for a spec1.in file, using NIRSPEC's low resolution mode with the NIRSPEC3 (J band) filter and a cross-disperser setting of 34.08 degrees, follows:

1.152818
1.161726

1.169121
1.177002
1.198820
1.206964
1.246280
1.269268
1.291555
1.322286

Do not leave any blank lines at the end of the ASCII file. Each entry in this example list is the wavelength in **microns** of a neon arc lamp line observed in the J band. This ASCII file consists of one entry per line, followed by a carriage return.

To identify the wavelengths of the prominent arc lamp lines in a given spectrum, NIRSPEC users should compare an arc lamp image to the NIRSPEC EFS overlay after loading the appropriate parameters into the EFS fields for slit, filter, etc. Approximate wavelengths on the detector image may be read off while parsing with the cursor. A rough identification can also be made using the formulas for the central wavelengths in each order (§1.2) and a linear approximation to the dispersion. A similar procedure will be required for other instruments.

It is not unusual to observe many lines in an arc lamp spectrum which do not have corresponding identifications in the EFS overlays and vice versa. Use caution when making line identifications; this is the most challenging aspect of spectral data reduction.

Because of the paucity of strong lines when observing at high dispersion, all available arc lamps are turned on at once in NIRSPEC's echelle mode to give a composite arc spectrum. In this case, the wavelengths of the identified lines in spec1.in might represent several different species, *e.g.* neon, argon, krypton and xenon. In the low resolution mode, usually only one arc lamp at a time is used to create a reference spectrum. Typically, more than one arc spectrum is taken; usually a neon lamp and an argon lamp. In this case, to use both the neon and argon exposures to create the most accurate dispersion solution possible, the file spec1.in would contain the wavelengths for the neon lamp and spec2.in for the argon lamp. This improves the precision of the dispersion solution.

Note on using OH night sky emission lines for wavelength calibration and dispersion. In the previous sections, both arc lamp lines and OH night sky lines have been discussed as useful for reference. In the following sections, the OH night sky line option will not be explicitly stated, but is implicitly understood. In practice, when running REDSPEC, the OH night sky emission lines can be used to replace the arc lamp lines by substituting either an OFF-source sky frame **or an ON-source data frame** for an arc lamp frame. Although, in the latter case, spectral data from the target will appear in the frame superimposed on the OH night sky lines, it runs in the dispersion direction, perpendicular to the slit. The OH night sky lines fill the slit and run in the cross-dispersion direction.

3.2 Parameter File

Section Summary

→ (1) Start IDL in the current data reduction subdirectory by typing **idl**
→ (2) Type **parfile** at the IDL prompt to invoke the PARFILE GUI
→ (3) Fill in PARFILE fields and click on "Done" when complete

To load the parameter file, which specifies the FITS file names, the calibration star effective temperature, and the system paths to the FITS files, the PARFILE module must be called in the IDL environment. For example, although the current directory may be */data/1/user/reduced_2001/star1/order48/*, the path to the FITS files might be something like */data/1/user/raw/01nov01/spec/*. The latter path must be specified in PARFILE, abutted by the filenames for each individual field.

Launch IDL from the current subdirectory by typing **idl** at the prompt. (Recall that all the data reduction products will be stored in this subdirectory.) Depending on the user's operating system and hardware, the color tables of the image display may be flawed. If display problems occur when viewing images, try typing **device, true_color=xx** at the IDL prompt, substituting the monitor display color depth for "xx" (try 16 or 24, for example). **This MUST be done at the START of the IDL session, otherwise it will have no beneficial effect.**

Loading the parameter file:
Type **parfile** at the IDL prompt (IDL is case insensitive). The PARFILE GUI will come up (Fig. 1). Use the "Make window narrower" option that appears above the target column to resize the GUI if necessary. The left hand column refers to the target data and the right hand side to the calibrator star data. To browse directories and fill fields, click on the browse buttons and select the desired path and files, or click on the field directly and manually enter path/file without browsing.

At the top left of the PARFILE GUI a "Help" button is available which invokes a popup window listing the required input files for each section of REDSPEC (Fig. 2). This popup may be dismissed with the "Done" button at the top left of the HELP GUI. In general, if a field in the CALIBRATOR column is left blank, REDSPEC will automatically read the target field for the corresponding item. The individual PARFILE fields are defined below.

(1) spatial map:
An output file created by running the spatial mapping routine, spatmap.pro (see §3.3).

(2) spectral map:
An output file created by running the spectral mapping routine, specmap.pro (see §3.4). The specmap.pro uses the spatial map file found in the current directory when it runs. The default names for the spatial and spectral map outputs are spat.map and spec.map for the target, and spat.map.cal and spec.map.cal for the calibration star. These default file names

will appear in the top two fields the first time PARFILE is called in a new subdirectory. These files will be overwritten if spatmap.pro and specmap.pro are called again from an IDL session in the same subdirectory.

If no NIRSPEC mechanisms were moved between the target and the calibrator star observations, and as a result the same set of flat and arc lamp frames were observed for both, then their spatial and spectral maps will be identical. In this case, the spatial map and spectral map fields in PARFILE under CALIBRATOR should be left blank; the filenames spat.map and spec.map will then be used as the default.

(3) flat, (4) dark, (5) arc 1, (6) arc 2:
Division of data by a flat field accounts for differences in the pixel to pixel response of a given detector. A dark frame is subtracted from the flat in order to account for the detector bias (see §1.1). The arc lamps are used for wavelength calibration and for determining the dispersion solution at a given grating setting, as discussed in §3.1.

(7) reference arc, (8) ref. spec map:
When running REDSPEC for the first time for a particular NIRSPEC setup, these fields should be left blank in both columns. Otherwise, these fields may be filled with the paths to and names of an arc lamp FITS file and a reference spec.map file, respectively, from a previous reduction involving the same NIRSPEC settings. If these fields are specified correctly, when SPECMAP is called in the current reduction, the arc lamp line identifications from the previous reduction will automatically appear. If two arc lamp line reference files, spec1.in and spec2.in, were used in the current and previous reductions, then automatic identifications for both will appear.

If the previous reduction was made on a different night, it is likely that a shift of a few pixels will occur in the columns where arc lamp lines of a particular wavelength fall on the detector. REDSPEC will take this shift into account unless it is greater than 20 pixels. It is important to examine the automatically identified lines for precision (see §3.4).

(9) nod 1, (10) nod 2:
Paths and filenames for exposures taken at the two slit positions, or ON−OFF source, for the target and calibrator star spectra. The order does not matter (i.e. nod 1 can be the NIRSPEC A or B nod position).

When observing an extended target, it is necessary to obtain two nod position spectra for the calibrator star even though there is data for the target object only in one nod position. This is a requirement for proper spatial rectification of the data. Since the single trace of an ON source observation is not suffient for spatial rectification, **do not change the NIRSPEC setting between observations of the extended target and the calibration star**. This ensures the best possible rectification.

(11) T_eff (CALIBRATOR column only):
This field is for the corresponding temperature of the telluric standard star (i.e. for an A0V star, 9480 K).

When all the relevant fields are completed, click on "Done" to close PARFILE. PARFILE automatically creates an ASCII file (called "files.in") outside of IDL in the data reduction subdirectory. To view this from within the IDL environment, type **$more** at the IDL prompt (for UNIX operating systems).

3.3 Spatial Map

Section Summary

→ (1) Type **spatmap** (or **spatmap,/cal**) at the IDL prompt.
→ (2) Click with the left mouse button at two locations to clip out order (echelle mode) or eliminate unilluminated pixels (low resolution mode). Click on "Done" to exit.
→ (3) Select desired parameters if different from defaults; enter clip parameter and **hit return** afterwards. Activate "Display Fit" if needed.
→ (4) Click on spectral traces to fit polynomial to data. Click on "Done" to exit when a satisfactory fit has been found, after adjusting parameters as necessary.
→ (5) Dismiss rectified image and filename popup.

Launching SPATMAP:
To begin the data reduction process, type **spatmap** at the IDL prompt. The code will automatically determine whether the data were taken in echelle or low resolution mode by checking the FITS header for NIRSPEC keywords. If you are using non-NIRSPEC data then this step will cause an error message. While spatmap is running, such status messages will be displayed in the window from which the code was called. It may be useful to check these messages in case of problems or to monitor progress.

The SPATMAP GUI window will appear showing an image of the arc lamp lines (Fig. 3). Use the vertical bar at the right side of the display to scroll. A small magnified window appears at the top left. If desired, the color stretch may be changed to logarithmic by clicking on the Log icon above the image. The contrast may be adjusted using the two sliding bars above the image to the left of the Log option; these control the clipping of the high and low intensities in the image. The location and value of your current pixel appears just to the right of the magnification box. Use the XLoadCT option to modify the color map if desired.

Obtaining a cross cut (optional):
At ANY point during the data reduction process a box may be drawn in the main GUI windows to show a vertical or horizontal cross cut for examination of the data. Use the **right hand mouse button** to draw any size box desired. A popup window will display the cut, automatically integrating over the columns or rows. The maximum and minimum values may be adjusted. A postscript plot of the cut can be created if desired by clicking on "Postscript". This saves a file called cut.ps for printing. **This file will be over-written by the next cut for which the postscript option is activated, so it should be renamed or printed immediately.** To cancel the popup, click on "Close". If an outline of the box which was drawn for the cross cuts persists and interferes with the main GUI window, click on the GUI with the right mouse button.

Isolating an order:
In the main SPATMAP window, use the left mouse button, to isolate the region of interest for this reduction by clicking with the cursor above and below this sector. Dashed lines will appear to indicate the selected boundaries. In echelle mode, this means bracketting the order of interest, for which the arc lamp wavelengths have already been specified in spec1.in. Because the orders are typically curved, delineating the boundaries might involve inadvertantly including some fraction of the neighboring orders; avoid including more than necessary.

For the low resolution mode, this step involves cutting out the unused pixels outside the broad swath that contains the data, since these extra pixels slow down the code. SPATMAP only recognizes the last two left mouse button clicks, so mistakes can be corrected by clicking again to re-define the two boundary lines. When the best pair of dashed lines have been selected, click the left mouse button on "Done". The GUI will disappear and the code will discard the pixels outside the clipped region.

Spatial Mapping:
In a few seconds, another GUI will appear with an image of the spectral traces of both nod positions, created by summing an $A + B$ pair of frames, so both traces of an on-slit pair appear positive and night sky OH emission lines have been summed rather than subtracted. For an ON$-$OFF pair, the target and background will appear summed, showing just one trace. This GUI, shown in Fig. 4, is for the purpose of spatial mapping. It fits only $1 - 2$ traces at a time. The image display can be adjusted with the slider bars and the parameters (order, height and width) set as desired. Setting the Sigma Factor is an important step. Data with a value greater than Sigma Factor $\times$ 1 standard deviation will not be used in fitting a polynomial to the spectral trace. For low resolution mode, a value of 2.5 is recommended. For echelle mode, a higher number, such as 5, may be better. **It is necessary to hit ENTER after typing in this value !** Otherwise the value will not be entered into the code. The Trim Fraction controls the fraction of data to be trimmed out before calculating an average and the Minimum Fraction parameter sets the minimum for the amount of data that should not be clipped out. Default values appear in all fields when the SPATMAP GUI comes up. Depending on the data quality, different values for these parameters may be optimal under different conditions. **Remember to hit return in the box after altering any of these values!**

If the calibrator star nod 1 and nod 2 fields are specified, it is these traces which are used when SPATMAP is called. If the calibrator star and the target were not observed on the same part of the slit, or if the NIRSPEC settings were changed in between the target and calibrator star observations, then the calibrator star nod 1 and nod 2 fields should be left blank when calling SPATMAP so that the traces used for the target spatial map are those of the target. For observations in the ON $-$ OFF mode, however, where only one trace was observed for the target, it is necessary to use the two calibrator star traces. For this reason, it is important not to change the NIRSPEC settings in between observations of the target and calibrator star when observing in ON $-$ OFF mode.

Click once on each trace. Be sure to activate the ON $-$ OFF option for a single trace if this was the mode of observation. Wait for a line to appear down the center of the trace, indicating that the fit to the data is complete. If the "Display Fit" button is activated, a window will pop up displaying the polynomial fit to the spectral trace (Fig. 5). The coefficients of the fit are shown in the upper right hand corner of this pop up. A postscript option is available; the postscript output file will be called "trace_fit.ps". Subsequent postscript files for which this option is invoked will overwrite the original, so print or rename the file promptly.

If the polynomial fits are inaccurate and do not fall clearly along each trace, try adjusting the height and width parameters. If the seeing during the observation was poor, the height should probably be increased. If the signal to noise ratio of the data is poor, try increasing the width. Also try left-clicking on a different part of the trace, for example in the region where the fit is inaccurate. Different polynomial orders for the fits (1−4) may be selected by clicking on the number in the top left hand box.

If the automatic fit is not satisfactory after adjusting these parameters, a manual fit may be made after activating the "Manual Fit" at top and clicking on at least two positions (i.e., for a first order fit; number of clicks required is the polynomical order plus one).

Once satisfactory fits have been found to the trace(s), click on "Done". The GUI will disappear and in a few seconds the final, spatially rectified image (Fig. 6) will appear, showing straight, horizontal traces for the data. The color stretch may be adjusted as usual for viewing. Drawing a long, flat box around the straightened traces (with the right mouse button) may help to verify the quality of the rectification. This GUI is for verification only; click "Done with SPATMAP" after inspection. A popup window will appear stating that the spatial map has been saved as "spat.map". Click "OK" on the popup. SPATMAP is now complete.

Spatial mapping for calibration star:
To run spatmap for a calibrator star, for the case in which the NIRSPEC settings have been moved between the target and calibrator observations, or if the target and calibrator were observed on different pixels on the slit, follow the same procedure as described above except use the command *spatmap,/cal* to call the code. SPATMAP will now read and write files from the CALIBRATOR column in PARFILE.

3.4 Spectral Map

Section Summary

→ (1) Type *specmap* (or *specmap,/cal*) at the IDL prompt
→ (2) Identify wavelengths of some arc lamp lines and fit curvature polynomials to each line
→ (3) Click on "Trail Lambda Fit" to check dispersion fit
→ (4) Change line identifications (after closing Trial Fit popup) as necessary, eliminating lines if required
→ (5) When a good lambda fit is obtained, save the postscript file of the fit if desired, click on "Lambda Fit" button in main SPECMAP GUI and "Done..." in subsequent GUI.

Launching SPECMAP:
At the IDL prompt, type *specmap*. The SPECMAP GUI will now appear with an image of the arc lamp lines to be identified and a list of the wavelengths of those lines as specified in spec1.in on the right hand side (Fig. 7). If two files, spec1.in and spec2.in, were used, and two arc lamp FITS files were specified in PARFILE, then two GUIs will come up, one for each arc spectrum. The wavelength list in the GUI corresponding to arc 1 is spec1.in and that corresponding to arc 2 is spec2.in. As usual the Log and color stretch bars are available.

The order of the polynomial fit to the individual lines may be selected (from 1−3) using the box on the top left. **If the line fit order is changed after identifying the lines, all identifications will be lost.** The top center boxes may be adjusted for the height and width of the fit to each line; for faint lines, it may be helpful to increase the fit height if necessary. For fitting lines that fall close together, decreasing the fit width may be required. Higher precision can be obtained using a larger fit width. This may be tested using the "Display Arc Lamp Fit" option. This option is extremely useful for the determination of the optimal polynomial fit order to the individual arc lamp lines. A postscript option is available on this pop up. The resulting file will be called "line_fit.ps", and will be overwritten by subsequent invoking of this postscript option unless the name is changed. The clipping parameters are the same as defined in §3.3, however the optimal values may be different here because the arc lamp line data is inherently different from the spectral trace data which was being fit in SPATMAP. Default values appear when the GUI comes up. **Remember to hit enter in the box after changing any of these values!**

If the reference arc and the ref. spec map fields in PARFILE were specified, the arc lamp line identifications will appear automatically. In this case, it is not necessary to tap the lines if the fits look good. Activating the buttons for the list of different arc lamp line wavelenghts on the right will highlight the automatic fit to the particular line, allowing for careful examination.

Tagging a line:
To tag a line in the image with a particular wavelength, click on the button to the left of a wavelength that appears in the list at the right hand side of the image. This activates that wavelength. Then click on the corresponding line and wait until a fit appears. The "+" signs on the tagged lines will appear at 20 pixel intervals. Then proceed to the next wavelength in the list on the right and to the next line in the spectrum. Be sure to click on the button to activate the particular wavelength or else the code will fit the new line to the previously activated wavelength. **If using two arc line files, and the "Display Arc Lamp Fit" option, it is necessary to tag a line in arc 1 first before proceeding to tagging lines in arc 2.**

It is NOT necessary to use all the wavelengths or all the lines! There are often some unidentified lines and some wavelengths with no obvious corresponding features. It is also prudent to avoid saturated arc lamp lines when possible, as these will produce inaccurate results. As described in §2, to identify the wavelengths of the arc lines, the NIRSPEC EFS arc lamp overlays are useful. A Thorium-Argon-Neon cathode lamp spectrum is also available at **http://www.noao.edu/kpno/phoenix/**. To deactivate a line so that it is *not* used in the dispersion solution, click on the box to the right of the wavelength to uncheck it.

Immediately above the spectral image the x and y pixel location appears in parenthesis and may be used as a guide, in tandem with the NIRSPEC EFS, for identifying the wavelengths of the arc lines. **It may be helpful to begin with only two or three robustly identified lines for the first trial lambda fit, since after one trial the wavelength of each column in the spectrum image will also be displayed next to the x and y position.**

Trial dispersion solution:
The order of the dispersion solution (lambda fit) is controlled by the box at the top on the right ("lambda fit order"); orders 1−4 are available. The dispersion is determined for every row of the spectrum; the residuals in the trial fit will depend slightly on the row chosen. Fig. 7 shows an arc lamp spectrum for one order of high resolution data with four lines identified. When satisfied with the line identifications, click on "Trial Lambda Fit" at the bottom of the wavelength list and then click on any row in the image.

The Lambda Fit GUI will now appear showing the arc lamp spectrum and a plot of the fit superimposed (Fig. 8). The dispersion solution is determined, for each row, to the *fitted* positions of the individual arc lamp line fits. If the Log scale option was used in the SPECMAP GUI, the spectrum will appear on a log scale as well. A cross will mark the location of the line (λ *versus* pixel number) with respect to the fit. All lines used will be numbered as in the main SPECMAP GUI; the line numbers and the wavelengths are printed on the right hand side of the popup for reference. The fit coefficients appear at the top left. The value of "Y" is the row number relative to the spectrum image in the main SPECMAP GUI. The offset of the line in pixels from the fit is printed next to each cross. For a good fit, this residual should be less than $\sim$0.1. Examine the residuals to ensure that this is the case. This plot may be saved and printed as postscript by clicking on the "Postscript" button. A file called "lambda_fit.ps" is created. Maintaining a record of the final fit by printing this graph is valuable. Unless the name of this file is changed, the next time this postscript option is invoked, it will be overwritten. When finished viewing the fit, click on "Close".

Dispersion solution − lambda fit:
After experimenting with the parameters (line fit order, line fit height and width, lambda fit order, etc.), when a good fit has been established, click on "Lambda Fit" to calculate the final dispersion solution. The GUI will close. Shortly afterwards a new, spectrally rectified image GUI will appear (Fig. 9); even if two arcs were used for the dispersion solution, only arc 1 will appear at this stage. After examination, click "Done with SPECMAP". A pop up will announce that the spectral map has been saved as "spec.map" (or "spec.map.cal" if the /cal option was used). The specmap procedure has now finished.

If two arc spectra are used, follow the above procedure as far as testing the line identifications with "Trial Lambda Fit" with one of them. Identifying the wavelengths in the second arc spectrum is easier since after running a "Trial Lambda Fit" on arc 1, the reference wavelength of the columns will appear above the image in the arc 2 spectrum. When finished with the arcs 2 identifications, clicking on "Trial Lambda Fit" will produce a dispersion solution popup derived from the information in both arc spectra. Note that the residuals using two arc spectra, if the lines have been identified correctly, are smaller than with just one arc spectrum. Once the lambda fit is satisfactory, exit as described above.

If it is necessary to run specmap for the calibrator star as well, call the procedure using **specmap,/cal** and follow the same procedures as outlined above.

3.5 REDSPEC

Section Summary

→ (1) Type **redspec** at the IDL prompt
→ (2) On the pop up, select options for the spectral extraction and click "Start"
→ (3) Code checks for saturation in data; continue or abort
→ (4) Clip out calibrator spectrum (if using calibrator star)
→ (5) Remove fringing from calibrator if necessary
→ (6) Remove intrinsic features in calibrator spectrum if necessary
→ (7) Clip out target spectrum
→ (8) Remove fringing from target if necessary
→ (9) Check results of final spectum

With the completion of the spatmap and specmap procedures, the information needed to rectify the image data is now available, and the main REDSPEC procedure can now be run. At the IDL prompt, type **redspec**.

REDSPEC control menu:
The first GUI to appear is a control menu for selecting the desired processes, such as the saturation check, fringing removal, etc. (Fig. 10). Select the desired parameters (if a check appears in a box, the selection is active; all selections are active as default). The interpolation option, second from top, is the alternative to a more sophisticated mapping algorithm. The difference between the results of these two methods of rectification is on the order of 1%; the mapping algorithm takes longer to run. If the box to the left of CALIBRATOR is not checked, then the calibration star will not be used at all in the reduction. Once all desired selections are activated, click the "Start" button at top to launch the code. In the following description, it will be assumed that all of the options are selected.

Saturation check:
If any saturation (> 18,000 counts per pixel on the spec detector) has occurred in the spectral data or flat frame exposures, then the first image(s) to appear will display the saturated frame(s) (Fig. 11). **Any saturated regions of the flat will appear as bright red.** The user may decide to abort the reduction or continue, both of which will close the GUI. Note that flat field exposures taken with the long slit (24″) in echelle mode, using long integration times, may show saturation in the areas of order overlap. If no saturation has occurred, the saturation check GUI will not appear.

REDSPEC:
The main body of the code will now run and all files will be rectified. The REDSPEC –

Calibrator GUI will appear (Fig. 12) if the CALIBRATOR option has been selected. After processing of the calibrator star, the target will be processed, thus the following description is general to both. To define the spatial extent of the spectrum for each nod position of the calibrator star, set the clip height with the sliding bar at the top right. A larger clip height will be needed under poor seeing conditions when the two-dimensional spectrum is spread out more in the spatial dimension, or for brighter sources. Plotting a vertical cut across the data helps to assess the appropriate clip height. The color stretch may be adjusted as usual.

It is important to cut out the spectra carefully using the magnification window at the top left to help set the cursor precisely in the CENTER of each trace. Using the left hand mouse button, click the cursor on the trace center. Set the Nod1−Nod2 or ON−OFF option as appropriate; only the last two clicks, or last click, for the former and latter, respectively, are retained, so mistakes can be corrected with additional clicks. When satisfied with the results, click on "Done". The GUI will close.

Fringing:
The REDSPEC – FRINGING GUI will now appear (Fig. 13). In the top panel is a plot of the power spectrum of the calibrator star. Fabry-Perot-like fringing internal to the instrument is sometimes apparent in high resolution spectra of very bright stars, or when using NIRSPEC behind the AO system (see the NIRSPEC+AO FAQ page). A spectrum of the calibrator, created from an unweighted sum of all the rows selected in the bottom trace from the previous GUI, appears in the bottom panel. If fringing is apparent in the spectrum in the lower panel, the corresponding spike may be identified in the power spectrum. To remove the fringing, click once on either side of the feature in frequency space (with the left hand button) and then click on "Remove Fringing". The revised power spectrum will be overplotted in red in the top panel, and the resulting filtered spectrum in red in the bottom panel. If the results are unsatisfactory, they may be undone by clicking left on the "Undo" button. A postscript option is available, producing a file called "fringing.ps". Rename the output so that it is not overwritten if this postscript option is selected again. When satisfied with the results, click left on "Done". The GUI will close.

Removal of intrinsic calibrator features:
The spectrum of the calibrator star will now appear in the REDSPEC – CALIBRATOR FEATURES GUI (Fig. 14). This may be used to eliminate spectral lines intrinsic to the atmosphere of the calibrator star. Click the left mouse button once on each side of an intrinsic spectral feature and then click left on "Remove Calibrator Feature". REDSPEC uses linear interpolation to remove these features. Be sure of the identification of the instrinsic lines and do not remove terrestrial features. If the interpolation is not satisfactory, click on "Undo" and repeat the process. The boundary width which is averaged to form the end points for the interpolation may be adjusted in the slide box at the top right. The GUI will disappear.

Target spectral extraction:
The REDSPEC – Target GUI will now come up (Fig. 15). Follow the steps described above for the calibration star. REDSPEC will check for fringing in the target star, but the option of intrinsic feature removal does not run for the target.

The final display is of the extracted spectrum (Fig. 16). The units are F_λ (because the black body is provided in units of B_λ; see §3.2, item 11) *versus* λ, where each pixel in the dispersion direction represents an equal interval of $\Delta\lambda$. The maximum and minimum can be set for the Y-axis by entering values in the appropriate boxes and hitting the carriage return. This final spectrum represents a science quality product ready for analysis such as flux calibration, obtained by scaling the F_λ values to absolute values by integrating over a known passband and matching to photometry. A postscript option (producing a file called "tar.ps") is available; rename the output so that it is not overwritten if this postscript option is selected again. To close this GUI, left click on "Close". To quit IDL, type **exit**.

Data reduction products:
Definitions of all data reduction products saved in the subdirectory from which IDL was launched are provided below:

tar.fits = fits file containing the two dimensional, rectified target spectrum
cal.fits = fits file containing the two dimensional, rectified calibrator star spectrum
tar.dat = ascii file containing the dispersion solution, the calibrated (i.e. divided by calibrator star spectrum and multpied by blackbody of T_eff) target spectrum (average of both nods), the spectra of the individual nod positions, and the difference spectrum of the two nod positions
cal.dat = ascii file containing the dispersion solution, the calibrator star spectrum (average of both nods), the spectra of the individual nod positions, and the difference spectrum of the two nod positions
spat.map = map used for target spatial rectification
spat.map.cal = map used for calibrator spatial rectification if necessary
spec.map = map used for target spectral rectification; the 5th number in the header gives the wavelength of the dispersion solution at the boundary between the 511th and 512th pixels; the 6th number in the header is the value of microns per pixel
spec.map.cal = map used for calibrator spectral rectification; the 5th number in the header gives the wavelength of the dispersion solution at the boundary between the 511th and 512th pixels; the 6th number in the header is the value of microns per pixel
files.in = data file which will be read the next time PARFILE is called from an IDL session launched from this subdirectory; if not pre-existing, will be created when PARFILE runs
.ps = any postscript files which were created during the data reduction

3.6 RECTIFY (Optional)

To obtain rectified data without running REDSPEC, use the RECTIFY procedure. For example, if a user wishes to apply an optimized extraction process to rectified data, it is unnecessary to run the final REDSPEC module; after obtaining appropriate spatial and spectra maps, RECTIFY may be used instead. This requires running SPATMAP and SPECMAP first. RECTIFY is called in the following manner at the IDL prompt:

rectify,'path/filename.fits',outputimagename

where outputimagename is an IDL array and must be saved, either with save,outputimagename,/xdr,file='outputimagename.idl' (in which case the file may be restored to an IDL session with the restore,'outputimagename.idl' command) or with writefits (syntax: WRITEFITS,'outputimagename.fits', outputimagename)

4 APPENDIX

Summary of IDL procedures used in REDSPEC code:

(1) parfile.pro – calls readpar if there is a "files.in"; creates new "files.in"
(2) readpar.pro – reads files in (as many as there are fields)
(3) spatmap.pro – calls readpar, displines, pickcal, spatrect, final
(4) displines.pro – shows dashed lines
(5) pickcal.pro – shows cut out of cal star; most important part of spatmap
(6) spatrect.pro – rectifies spatial dimension
(7) final.pro – displays spatially rectified image
(8) specmap.pro – calls picklamp, picklamp_2, final, readpar
(9) spatrect.pro – rectifies spatial dimension
(10) picklamp.pro – shows cut out of lamp image; identifies lamp lines
(11) picklamp_2.pro – used when there are two lamp iamges
(12) refshift.pro – calculates amount of shift when using a ref spec map (called from picklamp.pro)
(13) specrect.pro – rectifies spectral dimension
(14) final.pro – displays spatially & spectrally rectified image
(15) redspec.pro – calls readpar, displines, fixpix, pipe
(16) pipe.pro – core of code, calls spatrect and specrect; these two contain the rectification algorithm
(17) fixpix_rs.pro – cleans bad pixels (also called from spatmap and specmap) (fixpix.pro was written by Tom Murphy)
(18) fringe.pro – uses hanning filter
(19) rmline.pro – removes spectral features inherent to the standard star
(20) spatrect.pro & specrect.pro – rectify the image
(21) checksat.pro – checks for saturated images
(22) clip.pro – controls quality of data used in polynomial fits
(23) imdisp.pro – image display tool; independent from the above sequence
(24) rectify.pro – performs rectification without data reduction