

Spextool User's Manual*

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1 Introduction

Spextool (SPECTral EXtraction TOOL) is an Interactive Data Language (IDL)-based data reduction package written by Michael Cushing, William Vacca, and John Rayner to reduce data obtained with **SpeX** on the NASA **Infrared Telescope Facility (IRTF)**.

SpeX is a $0.7\text{--}5.3\text{ }\mu\text{m}$ ¹ medium-resolution ($\lambda/\Delta\lambda \approx 2000$), cross-dispersed spectrograph. The entire 0.7 to 5.3 μm wavelength range can be covered with two cross-dispersed modes, the short-wavelength cross-dispersed mode (SXD), and the long wavelength cross-dispersed mode (LXD), with a 15''-long slit. There are also single-order (e.g. each photometric band) long-slit (60'') modes and a high throughput low-resolution prism mode that covers the 0.7-2.5 μm wavelength range with either a 15''- or 60''-long slit. A more detailed description of SpeX can be found in **Rayner et al. (2003, PASP, 115, 362)**. SpeX underwent an upgrade in early 2014 so the descriptions of the arrays and electronics in the paper are no longer applicable. Please see §1.2 for a summary of the changes or the **upgraded SpeX manual** for a more detailed description of the changes. In addition, since 2012 a CCD imager known as MORIS (**Gulbis et al. 2011, PASP, 123, 461**) is mounted to the side of SpeX. MORIS is fed by an optical reflecting dichroics inside SpeX. MORIS can be used for optical guiding and for optical photometry simultaneously with SpeX.

Spextool was designed to reduce data taken with a 15''-long slit in the SXD, LXD, and prism modes. A detailed description of the procedures incorporated into Spextool can be found in **Cushing, Vacca, & Rayner (2004, PASP, 116, 362)**. A description of the telluric correction procedures are described in **Vacca, Cushing, & Rayner (2003, PASP, 115, 389)**. Note that while a few of the procedures have changed in detail since these papers were published, the general descriptions of the steps and overall philosophy remain the same. This manual is a compilation and amplification of the ASCII help files written by Bill Vacca in 2000-2001 that were included in Spextool versions earlier than v4.0.

1.1 References

We require users to reference the papers listed below if they use any of the following:

- **SpeX:** **Rayner et al. (2003, PASP, 115, 362)**
- **Spextool:** **Cushing, Vacca, & Rayner (2004, PASP, 116, 362)**
- **Telluric Correction:** **Vacca, Cushing, & Rayner (2003, PASP, 115, 389)**

Note: *Although the telluric correction algorithms are contained within the Spextool package, we still ask users to reference both the Spextool and telluric correction papers.*

¹Prior to 2014, SpeX used an InSb array in the spectrograph camera and thus was sensitive out to 5.5 μm .

1.2 Overview of SpeX

Spextool is designed to reduce data obtained with both the pre-upgrade SpeX (2000-2013) and the upgraded SpeX (2014-). For a detailed description of the pre-upgrade SpeX, please see Appendix A.

1.2.1 Detectors and Array Controllers

In early 2014, SpeX underwent an upgrade that was centered around the installation of a new 2048×2048 HgCdTe HAWAII-2RG array in the spectrograph camera (the old 1024×1024 InSb array was moved to the guide camera). The upgraded SpeX uses two generic PCs running CentOS/Linux for Bigdog and Guidedog. The PCs are located in the telescope control room and are connected by optical fibers to Astronomical Research Camera (ARC) Generation 3 controllers mounted to the cryostat, one each for Bigdog (spectrograph - 2048×2048 H2RG array) and Guidedog (guider - one quadrant of a 1024×1024 Aladdin array). The H2RG array requires a 12-slot housing containing one ARC-22 fiber optic timing board (a DSP board performing the same function as the the DSP board in the old system), one ARC-32 IR and CCD clock driver board, four 8-channel IR video boards (16-bit A/Ds, pre-amps, and biases), and a separate bias board. The separate bias board is an in-house board that provides for better bias voltage control, replacing the bias function built into the video boards. Four video boards are needed to read out the 32 channels of the H2RG. The H2RG is wired for 32 outputs since we require integration times as short as 0.4 sec ($3 \mu\text{sec pixel}^{-1}$). The smaller InSb array requires a 6-slot housing containing one ARC-22 fiber optic timing board, one ARC-32 IR and CCD clock driver board, and one 8-channel IR video board (16-bit A/Ds, pre-amps, and biases). A separate bias board was is needed.

All channels of the 2048×2048 H2RG spectrograph array are read out simultaneously. Each channel reads out blocks of 64-pixel wide columns. Given slight variations in channel gain and 'burst' noise on read out this results in a distinctive array read out pattern at very low signal levels: a vertically striped pattern with slight offsets of a few DN between neighboring channels. The one quadrant of the 1024×1024 Aladdin guider array that is read out has the same eight column structure as before.

The H2RG spectrograph array has a gain of $2.44 \text{ e}^- \text{ DN}^{-1}$, a $15 \mu\text{sec pixel}^{-1}$ read noise of about $15 \text{ e}^- \text{ RMS}$ per CDS and about $5 \text{ e}^- \text{ RMS}$ for 32 NDRs. The blanked off dark current is about $0.08 \text{ e}^- \text{ sec}^{-1}$ (due mostly to thermals leaks). As a result of the much reduced image persistence in this array the effective dark current is not significantly different. The science quality Aladdin array now in the guider has a gain of $17 \text{ e}^- \text{ DN}^{-1}$ and a $7 \mu\text{sec pixel}^{-1}$ readnoise of about $60 \text{ e}^- \text{ RMS}$. The effective dark current is about $1.5 \text{ e}^- \text{ sec}^{-1}$ (due to a combination of thermal leaks and image persistence).

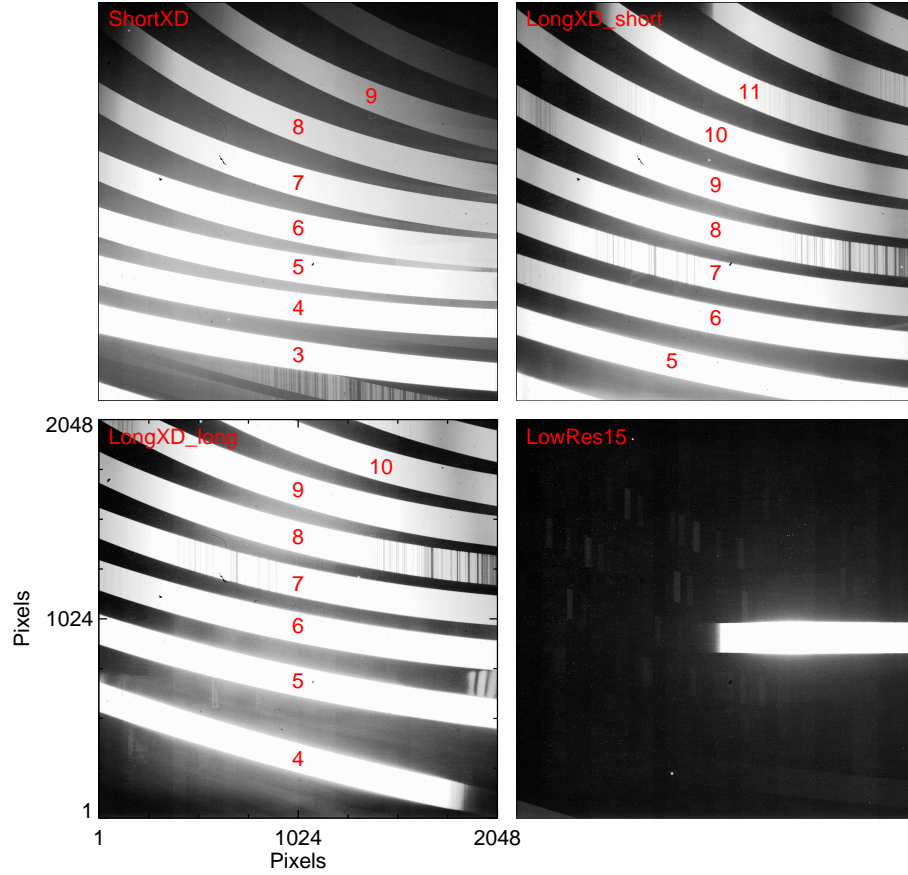


Figure 1: Flat-field exposures for the four upgrade SpeX modes compatible with Spextool.

1.2.2 Spextool and Instrument Modes

With a larger array format, the upgraded SpeX can grasp more orders and more wavelength coverage within each order. As a result, the three LongXD modes have been condensed into two modes, LongXD_short, and LongXD_long. Spextool can reduce SpeX data obtained with the ShortXD, LongXD_short, LongXD_long, and LowRes15 modes. Figure 1 show flat field exposures for each of these modes and Tables 1 give the wavelengths covered by each of the orders in the cross-dispersed modes. The LowRes15 mode consists of a single order dispersed with a double-pass prism and covers the wavelengths from 0.7 to 2.5 μm .

Table 1: XD Mode Wavelength Coverage for the upgraded SpeX

Order	Wavelengths (μm)		
	ShortXD	LongXD_short	LongXD_long
11	...	1.68–2.02	...
10	...	1.69–2.23	1.94–2.23
9	0.69–0.85	1.87–2.48	1.95–2.48
8	0.71–0.96	2.10–2.79	2.10–2.79
7	0.78–1.10	2.40–3.19	2.40–3.19
6	0.92–1.28	2.80–3.71	2.80–3.71
5	1.11–1.54	3.36–4.23	3.37–4.46
4	1.37–1.92	...	4.21–5.36
3	1.83–2.56

1.2.3 Data Format

The data are written to disk as multi-extension FITS files (MEF) that contains three extensions. The image contained in the zeroth extension is identical to the image written to disk by the original SpeX software. In order to understand what these data values actually represent, and what the images in the first and second extensions represent, it is instructive to inspect Figure 2.

Figure 2 which shows a schematic of the signal recorded by a given pixel as a function of time on a perfectly linear detection with the number of non-destructive reads (n_r) set to 3. After the array is reset to the bias level b , the array is read continuously every δt seconds. The sum of the first n_r reads provides an estimate of the *pedestal* level while the sum of the last n_r reads provides an estimate of the signal level. The pixel values in the zeroth extension of the FITS files is given by:

$$S = \sum_{i=1}^{n_r} p_i - \sum_{i=1}^{n_r} s_i \quad (1)$$

The image in the first extension is given by $\sum_{i=1}^{n_r} p_i$ while the image in the second extension is given by $\sum_{i=1}^{n_r} s_i$.

We note that in principle, each non-destructive read must be corrected for nonlinearity since each read occurs at a different location on the linearity curve. However, the linearity correction routines currently only work on the difference between the pedestal and signal reads. However, we do use the sum of the pedestal and signal reads to identify pixels that have counts beyond the linearity curve maximum.

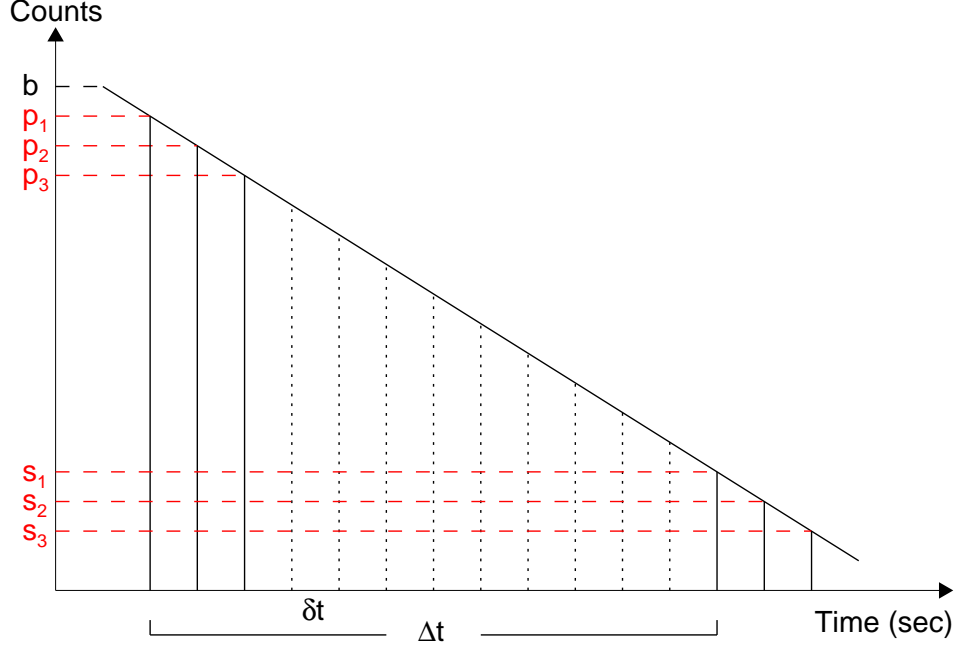


Figure 2: Schematic of how the upgraded SpeX array is read out. Δt is the exposure time, δt is the time between non-destructive reads, b is the bias level, p_i is the i^{th} pedestal read and s_i is the i^{th} signal read.

1.3 Spextool and Other Instruments

Spextool was initially designed to reduce data obtained with SpeX alone. However, because it has proven to be very popular and two of us (M.C.C. and W.D.V.) required reduction software for other spectrographs, the code has been expanded and modified to handle data from other instruments. Table 2 lists the instruments whose data Spextool can reduce. If you are interested in reducing data for one of these instruments, please contact Michael Cushing at michael.cushing@gmail.com.

Table 2: Spextool and Other Instruments

Instrument	Telescope	Limitations	Availability
SpeX	IRTF	SXD, LXD, prism	public
TripleSpec	Hale 200 inch	no optimal extraction	public
TripleSpec	APO	no optimal extraction	public
CorMASS	VAT	none	public
FIRE	Magellan	lowres	private
GNIRS	Gemini North	XD	private
FLITECAM	SOFIA	none	public
FORCAST	SOFIA	none	public
EXES	SOFIA	none	public

2 Installation and Overview

2.1 Backwards Compatibility

Version 4 of Spextool is backwards compatible with all spextool spectral FITS files generated by Spextool beginning with version 2. However, the calibration files generated by previous versions of spextool are not compatible with version 4 and therefore if the user wishes to re-reduce data with version 4 they will need to create new calibration files.

2.2 Software Installation

1. Spextool requires IDL 7.0 or later. We furthermore assume that the user has successfully installed IDL and can use it before he or she has installed Spextool.

***Note:** Simply starting up IDL is not necessarily an indication that IDL is installed properly. A good test is to attempt to launch the GUI `xloadct`. If IDL crashes, then IDL has not been properly installed.*

2. If the user is upgrading from a previous version of Spextool, please delete the previous version of Spextool (or move it out of your IDL path). Download the gzipped tar file from the SpeX website (<http://irtfweb.ifa.hawaii.edu/~spex/>) and unpack it. For example, on a Unix-based system you would type `tar zxvf Spextool.tar.gz` on the command line. This will create a directory called Spextool, which is hereafter referred to as the `packagedirectory`, and a number of sub-directories.
3. The user must now add the Spextool directory and all subdirectories to their IDL path. This can be accomplished in various ways.

- If the user has a single IDL directory that is searched recursively for IDL libraries, then simply place the Spextool package in this directory. If the user stores other IDL libraries in the same directory but must load them into the IDL path on a case-by-case basis (due to various dependencies), then Spextool may be loaded at any point in the IDL path.
- If this is the first time the user is installing an IDL package, we recommend creating a single directory, .e.g. `IDL`, into which the Spextool and other packages can be placed. Then the user must include this directory in their IDL path. This can be done in a number of ways, including adding the path to your `.idl_startup` file, or adding it to your `IDL_PATH` environment variable.

For example, on a Unix-based machine using the C shell where the environment variable `IDL_PATH` has already been defined, edit the `.cshrc` file to include the line:

```
setenv IDL_PATH +rootdir/IDL:$IDL_PATH
```

If the IDL_PATH environment variable has not been used previously in the .cshrc file, add the following to the file.

```
setenv IDL_PATH +rootdir/IDL/:'<IDL_DEFAULT>'
```

In both cases, the + sign tells the system to recursively search the subdirectories in the Spextool package.

Note: *It is crucial that all the subdirectories in the Spextool package be added to the IDL path.*

4. Spextool requires two additional IDL libraries in order to operate properly:

- **The Astronomy User's Library:** The main page is located at the following URL: <http://idlastro.gsfc.nasa.gov/homepage.html>. The user must install both the main library **and** the coyote routines required by the Astronomy User's Library (see below).
- **The Markwardt MPFIT Package:** The main page is located at the following URL: <http://www.physics.wisc.edu/~craigm/idl/idl.html>.

If the user has these libraries already installed on their system, then no further action is required and they can move on to the next step. If not, the user should download these packages and install them as described in step #3. Although in principle they can be contained with the Spextool directory structure, it is easier to upgrade Spextool if they are located in the IDL directory. The two astronomy libraries (some form of `astron.tar.gz` and `coyote_astron.tar.gz`) can be downloaded from this URL: <http://idlastro.gsfc.nasa.gov/ftp/>. The Last Modified date on the libraries should be no earlier than 14 Jun 2014. The MPFIT package can be downloaded from this URL: <http://www.physics.wisc.edu/~craigm/idl/listing.html>. The Last Modified date on the library should be no earlier than 14 Aug 2013.

For the convenience of users who will only ever use IDL for Spextool, we have included copies of these libraries in `Spextool/other/`. Simply uncompress these libraries in their current location and they will be found if the user has properly installed Spextool.

5. *An incorrect path is one of the most common causes of problems encountered in attempting to run Spextool for the first time.* The user can start IDL and type `mc_testspextoolpath` at the IDL prompt to test whether he/she has set the paths correctly.
6. On a Unix-based system, pop-up menu lists can be made to respond to mouse scroll wheel input by modifying a set of resources associated with the X11 windows environment. Add

the following to your `.Xdefaults` file:

```
*XmList.baseTranslations: #augment <Btn5Down>:ListNextPage()\n<Btn4Down>:ListPrevPage()\n\n*XmScrollBar.baseTranslations: #augment <Btn4Down>:\nIncrementUpOrLeft(0) IncrementUpOrLeft(1)\n<Btn5Down>: IncrementDownOrRight(0) IncrementDownOrRight(1)\n
```

and either restart your X environment or incorporate the changes by typing

```
> xrdp -merge $HOME/.Xdefaults
```

in a terminal. Carriage returns should only be placed after the “\n” characters. You can now use the scroll wheel on your mouse to move within popup text windows. Moving the wheel in any text window (e.g., help windows) or file selection window will now perform “page up/page down”. Moving the wheel while over a text scroll bar will move one line at a time.

2.3 Test Data

If the user wants to practice using Spextool with real data, they should download the gzipped tar file `uSpeXdata.tar.gz` from the SpeX website (<http://irtfweb.ifa.hawaii.edu/~spex/>) and unpack it. It contains SXD and LXD_long observations of the G2 IV star CD–23 17771A. The standard star used in these observations is HD 223352 (A0 V). The specific files included are given in Table 3. The data will be placed in the raw directory (see §3.2). Throughout this manual, we will refer to these data when giving examples of how to reduce data.

Table 3: Upgraded SpeX Test Data for CD –23 17771A

data type	prefix	SXD files	LXD_long files
flat fields	flat-	17–21	45–49
arcs	arc-	22	43–44
science .	spc-	1–6	23–32
standard	spc-	7–16	33–42

2.4 Overview of Reduction Steps

The Spextool package consists of multiple Graphical User Interfaces (GUIs) that allow the user to extract and calibrate their data. A list of the GUIs and their primary purpose(s) is given below; the name of each step is what the user types at the IDL command line in order to launch the appropriate GUI. All GUIs that plot data are resizable and the user can view this manual at any time by clicking the **Help** button in each GUI.

1. xspextool

- create normalized flat field images and wavelength calibration files
- apply non linearity correction to raw data and flat field correction
- pair subtract A and B images
- define extraction apertures positions
- trace object spectra
- background subtraction
- (optimally) extract spectra and wavelength calibrate

2. xcombspec

- combine individual extracted (multi-order) spectra

3. xtellcor (and xtellcor_basic and xtellcor_finish)

- perform telluric correction and flux calibration on extracted (multi-order) spectra.

4. xmergeorders

- merge telluric-corrected, multi-order spectra into a single continuous spectrum

5. xmergexd

- combine SXD and LXD spectra

6. xcleanspec (optional)

- clean a spectrum by removing or fixing bad pixels and smooth a spectrum

7. spex2text (optional)

- convert the Spextool FITS files to an ASCII file for further analysis with other software packages

2.5 Additional GUIs: `ximgtool`, `xvspec`, `xzoomplot`

In addition to the GUIs described above, there are three additional GUIs that the user can interact with, `ximgtool`, `xvspec`, `xzoomplot`.

2.5.1 `ximgtool`

`ximgtool` is a multi-buffer, resizable, array/FITS viewer which in appearance is based on the older `ximtool` display tool. Although `ximgtool` can be used as a stand-alone routine and has a rich set of features (see the Help menu), Spextool users typically only need to pan around the image and browse through the buffers. To pan around the image the user can use a mouse in the following way:

- Left mouse click - center at pixel and zoom in by a factor of two
- Middle mouse click - center at pixel
- Right mouse click - center at pixel and zoom out by a factor of two

The user can also use cursor commands to pan around the image. Simply type the following letters in the window to active the command.

- i- zoom **I**n by a factor of two
- o- zoom **O**n by a factor of two
- t- zoom **T**o fit the display window

Finally, the user can browse through the buffers using the cursor commands:

- f- to move (**F**orward) to the next buffer
- b- to move (**B**ackwards) to the previous buffer

2.5.2 `xvspec`

`xvspec` is a general-purpose, resizable, FITS viewer specifically designed to work with the spectral FITS files produced by Spextool. It can be launched at any time by typing `xvspec` at the IDL command line. The user can learn about the full list of cursor commands via the **Help** menu, but the primary way a Spextool user will interact with it is to view the **Flux**, **Uncertainty**, **S/N** spectra. `xvspec` can display the multi-order spectra in two ways: 1) the spectrum of each order is plotted

separately one on top of each other (i.e. “ladder”), and 2) the spectra are plotted on a single plot covering the entire wavelength range (i.e. “continuous”). The atmospheric transmission can also be overplotted in either mode using the **Plot** pulldown menu. In addition, the user can click on a spectrum (in either viewing mode) and `xvspec` will launch the `xzoomplot` GUI.

The user can also use cursor commands to interact with `xvspec`.

- a- to display the **A** buffer
- b- to display the **B** buffer
- f- to display the **flux** spectrum
- u- to display the **uncertainty** spectrum
- s- to display the **S/N** spectrum

2.5.3 `xzoomplot`

`xzoomplot` is a simple resizable GUI that allows the user to exam a single spectrum. The primary way to interact with this routine is with cursor commands which are summarized below.

- a - sets the **Absolute** plot range to the current x and y range
This is very useful if the spectrum has a bad pixel as this x and y range is what will be used when the user types ‘w’ rather than the true min/max of the spectrum.
- c - **C**lear any current cursor command
- i - to zoom **I**n in whatever zoom mode the cursor is currently in. For example, if the plot window is currently in the ‘x’ zoom mode, typing ‘i’ will zoom in
- o - to zoom **O**ut in whatever zoom mode the cursor is currently in
- w - to plot the **W**hole spectrum, i.e. the full range of the spectrum. By default the plot ranges are set to the minima and maxmima of the spectrum. However if the user has set the absolute range by using the ‘a’ cursor, then these values are used instead.
- x - enters the **X** zoom mode
Press and release left mouse button at lower x value and then again at upper x value.
- y - enters the **Y** zoom mode
Press and release left mouse button at lower y value and then again at upper y value.
- z - enters the **Z**oom mode
Press and release the left mouse button in one corner of the zoom box and then move the cursor to the other corner and press and release the left mouse button.

2.6 Common Cursor Commands

Many of the Spextool GUIs have interactive plot windows. The cursor commands described in the previous section can also be used in these GUIs.

2.7 Index & Filename Modes

The upgraded SpeX filenames have the format `prefixNNNNN.beam.fits` where `prefix` is a user defined prefix, `NNNNN` is a five digit number, and `beam` is the beam position, either `a` or `b`. For example, a flat field exposure would have the name `flat00001.a.fits` while a science exposure might have the name `spc00010.a.fits`.

The `xspextool` and `xcombspec` GUIs take advantage of this simple format by only requiring the user to enter the number of the filename required, e.g. `10` for a file called `spc00010.a.fits`. There are, however, times when it is more useful to simply provide the fullname of the file. To switch between the two methods of input, the user can switch the **File Read Mode** from **Index** to **Filename**. Of course if the **Index** mode is selected, the user must provide the prefix of the filename, e.g. `spc` for a file called `spc00010.a.fits`.

2.8 Combination Statistics

At various points in the process of reducing SpeX data (e.g. combining images or spectra), the user will be required to select a statistic with which to combine data. Below, we give a description of each statistic and its associated uncertainty estimate. For the robust statistics, a pixel value I_i is identified as an outlier if

$$\frac{|I_i - \text{med}(\mathbf{I})|}{\text{MAD}} > \text{thresh}, \quad (2)$$

where $\text{med}(\mathbf{I})$ is the median of the intensity values, MAD is the median absolute deviation given by $1.482 \times \text{med}(|\mathbf{I} - \text{med}(\mathbf{I})|)$, and thresh is the user set threshold value. The MAD is a robust estimate of the standard deviation and the constant 1.482 is defined such that if the random variable I_i follows a normal distribution, then $\text{MAD}=\sigma$ if the sample size is large. The default statistic is the Robust Weighted Mean with a clipping threshold of 8 (sigma).

- **Robust Weighted Mean:** A sigma clipping algorithm is used to identify outliers. The value at each pixel is then the weighted average of the good pixels and the uncertainty is given by the propagated variance.
- **Robust Mean (RMS):** A sigma clipping algorithm is used to identify outliers. The value at each wavelength is the mean of the good pixels and the uncertainty is given by rms deviation of the good pixels.

- **Robust Mean (Std Error):** A sigma clipping algorithm is used to identify outliers. The value at each wavelength is the mean of the good pixels and the uncertainty is given by the standard error on the good pixels (s/\sqrt{n}).
- **Weighted Mean:** A weighted mean and uncertainty of all the pixels are given at each wavelength.
- **Mean (RMS):** The value at each pixel is given by the mean and the uncertainty is given by the RMS deviation of the pixels.
- **Mean (Std Error):** The value at each wavelength is the mean of the pixels and the uncertainty is given by the standard error on the pixels (s/\sqrt{n}).
- **Median (MAD):** The value at each pixel is given by the median and the uncertainty is given by the median absolute deviation.
- **Median (Std Error):** The value at each pixel is given by the median and the uncertainty is given by the standard error around the median ((MAD/\sqrt{n})) of the pixels.
- **Sum:** The value at each pixel is given by the sum.

Note: The uncertainty spectrum typically looks very different if a (robust) weighted mean is chosen rather than a statistic that uses the RMS as a measure of the uncertainty. The reason is that the RMS measures the scatter between data and thus is sensitive to small changes in said data. This is particularly important when it comes to combining spectra as the spectra suffer from heterochromatic slit losses (see §4.3.3 for a more indepth discussion of this issue). Although the default statistic is a robust weighted mean, the user should be aware of these issues and choose their statistic appropriately.

2.9 Bitwise Set Flags

Spextool includes a bitwise flag array that give useful information for each output pixel. Currently Spextool uses only the first three bits and sets them as described in Table 4.

Table 4: Bitwise Flag Values

bit	value	color	Description
0	1	red	one or some of the values that went into this pixel were greater than the linearity correction maximum.
1	2	blue	one or some of the values that went into this pixel were identified as bad by Spextool and replaced using a model of the spatial profile.
2	4	cyan	one or some of the values that went into this pixel were fixed in the xcleanspec routine.

Table 4: Bitwise Flag Values

bit	value	color	Description
3	8	yellow	optimal extraction failed on this pixel.

The saturation level can be found under the LINCORMAX keyword in the instrument calibration file, e.g. `packagepath/instruments/uspex/data/uSpeX.dat`. Note also that if optimal extraction is used, then bad pixels are ignored and thus the first bit is rarely set.

2.10 Spextool FITS Files and Conversion to ASCII

Spextool outputs FITS files that contain a 4-D array of data consisting of sets of quadruplet arrays [npixels,4] of data for each aperture and each order, where each quadruplet is composed of an array for the wavelength [*,0], an array for the flux [*,1], an array for the uncertainty [*,2], and a bitwise set flag array [*,3] (see 2.9 for a description of the values). The quadruplets for each aperture are stacked behind one another, followed by the quadruplets for the next order, etc. If no orders have been skipped or deselected in the extraction process, the contents of aperture Y in order X can be found as follows:

```
lambda = array[*,0,( X - (smallest order number))*naps + (Y-1)]
flux = array[*,1,( X - (smallest order number))*naps + (Y-1)]
uncertainty = array[*,2,( X - (smallest order number))*naps + (Y-1)]
flag = array[*,3,( X - (smallest order number))*naps + (Y-1)]
```

For example, for an SXD file with two apertures, the wavelength array for aperture 1 in order 3 is located in array[*,0,0], the flux is in array[*,1,0] the uncertainty is in array[*,2,0], and the flag array is in array[*,3,0]. For aperture 2, the wavelength is in array[*,0,1], the flux is in array[*,1,1] the uncertainty is in array[*,2,1], and the flag array is in array[*,3,1]. For order 4, the flux for aperture 1 is in array[*,1,2], while the flux for aperture 2 is in array[*,1,3]. For order 5, the fluxes for the two apertures are in array[*,1,4] and array[*,1,5], etc.

The user may convert any FITS spectral files generated by Spextool into ASCII files that can be read by another programs required for further analysis in two ways. At the command line, simply run the program `spex2text` and follow the instructions, e.g.:

```
IDL> spex2text
```

The contents of the FITS file (including the FITS header) will be written to an ASCII file. An alternative method is to view the spectra(um) in `xvspec` and select **Write ASCII File** from the **File** menu. The user should then enter the output file name and hit return.

3 Spectral Extraction: xspextool

The `xspextool` GUI allows the user to flat field, extract, and wavelength calibrate spectra from raw data.

3.1 Choosing the Instrument

1. In order to load the correct calibration files and programs, Spextool must know what instrument was used to obtain the data. There are two ways to choose the instrument. We **strongly** recommend the first method but in circumstances where Spextool is installed in a common area (e.g., `/user/local/`) where individual users cannot easily modify files, the second method is required.

- This default instrument is stored in the file,

```
spextoolpath/data/Spextool_Instruments.dat
```

and should be changed each time the user wishes to reduce data obtained with a different instrument. Current choices are either `SpeX` or `uSpeX` (for upgraded `SpeX`) with the default being `uSpeX`. An instrument can be commented out with `#` character, e.g. `#SpeX`.

- The user can also pass the name of the instrument to `spextool` on the command line on start up, e.g.,

```
IDL> xspextool, 'SpeX'
```

If an instrument is passed on the command line, then it will override the instrument in the file `Spextool_Instruments.dat`. As noted above, we urge users to use the former method when at all possible.

3.2 Starting up and Loading the Paths

2. Start IDL and bring up the main Spextool GUI by typing `xspextool` at the IDL prompt, e.g.

```
IDL> xspextool
```

or if the user is switching instruments on the command line (as describe above),

```
IDL> xspextool, 'instrument'
```

Once the GUI has appeared, please check the title bar to make sure you are running the correction version (v4.1) and that the correct instrument is loaded.

Spextool assumes that flats and arcs obtained with the SpeX cal macros will have the file prefixes of "flat" and "arc", respectively. If your calibration files have prefixes different from this convention, or if your data were taken before Nov. 2000, then you will not be able to process these files with the Cal Panel (see §3.3). In such cases, you should restart Spextool in IDL as

```
IDL> xspextool, /FAP
```

where FAP is an IDL keyword that stands for "Flat and Arc Panel". This will launch Spextool with a different Calibration panel that allows the user to construct normalized flat field frames and the wavelength calibration images separately.

3. Click on the **Paths** button in the middle of the Spextool GUI. This will bring up the Paths Panel. Spextool will automatically load the paths last entered by the user. If this is the first time that Spextool is being run, or if the directories are different from the last time Spextool was used, the user will have to change the paths.

Spextool **requires** that the raw data, processed data needed for calibrations (e.g., normalized flats and wavelength calibration files), and completely reduced data will be kept in separate directories. Typically these directories will be called `raw` (for raw data), `cal` (for processed calibration files) and `proc` (for **processed** data files). Type or (click) the paths for these three subdirectories in the fields listed in the Paths panel. Spextool will remember these directories, so that next time you start Spextool these fields will be loaded automatically.

3.3 Flat Field, Wavelength Calibration, and Sky Frames

3.3.1 Flat Fields and Wavelength Calibration

Note: *Because of flexure and the variable nature of atmospheric absorption, it is recommended that each set of images of a given object be reduced with its own set of flats, arcs, and telluric standards.*

Note: *If your flat field and arc images files do not have the prefixes `flat` and `arc`, please see §11.1.*

4. Click on the **Cals** button in the middle of the Main GUI. This will bring up the Cal Panel with a table that can be filled with multiple sets of calibration files obtained using the pre-

defined SpeX calibration macros. Fill in the left-hand column labeled “Flat & Arc Files” by clicking on a line and then entering the file numbers corresponding to a full calibration set (which includes both the flats and arcs). In the case of the test SXD data, the user should enter 17–22, while in the case of the test LXD_long data, the user should enter 43–49.

Note: *You must hit return after entering the file numbers.*

If the data were obtained with one of the LXD gratings, the user must also provide a sky frame for each cal set because Spextool uses the night sky emission lines in the lower orders of the LXD modes for wavelength calibration (since these orders have either very weak or no arc lines). If the target corresponding to the cal set in question is an extended source (and thus sky frames were taken), type the file number of a sky image in the “Sky Files (LXD)” column of the table. If your target is a point source, enter the file numbers of an AB pair in the table (e.g., 45–46 for the pair `spc-00045.a.fits`, `spc-00046.b.fits` in the test data). Finally, type the sky file(s) prefix in the “Sky Prefix (LXD)” column (e.g., `spc-`). Spextool will then create a pure sky frame by computing

$$\text{sky} = (A+B) - \text{abs}(A-B). \quad (3)$$

If file numbers are not entered in the right-hand column, but are needed by Spextool, the calibration routine will display an error message and exit.

Click on the **Construct Calibration Frames** button at the bottom of the Cals Panel. Spextool will then create a normalized flat field, wavelength calibration, and a Quality Assurance (QA) file. In the case of the SXD test data, the files `flat17-21.fits`, `wavecal22-22.fits`, and `wavecal22-22-QA.eps` would be written into the `cal/` directory. The normalized flat field, wavelength calibration and spatial calibration images are displayed in `ximgtool` along with the location of the edges of the orders. The user can scroll through the three buffer by clicking ‘f’ for **F**orward and ‘b’ for **B**ackwards or use the pull down menus (see §2.5.1 for more information about `ximgtool`).

Note: *Pixels that were derived using raw data beyond the linearity maximum are flagged as red. The user should **not** use calibration frames constructed using data obtained beyond the linearity maximum.*

The cal generation process takes some time and incorporates a number of steps, including inspection of the files to determine the observing mode, scaling and combining the images, finding the edges of the orders, fitting a 2-D surface to each order of the flats, replacing bad pixels in the flats, and normalizing the flat by the 2-D surface, extraction of an arc spectrum, automatic arc line identification, and fitting of the identified lines to determine a wavelength solution. Spextool will not allow the user to do anything while it processes the

calibration files, but it will show you where it has found the individual orders in the images in `ximgtool`.

The two output FITS files are actually Multi-Extension FITS (MEF) files that can be viewed with `ximgtool` or any FITS viewer, e.g. DS9. The flat field file has four extensions. The zeroth extension contains the FITS header and all of the ancillary information necessary for extraction (see §10.1 for an example of the FITS header keywords added by `Spextool`), the first extension contains the normalized flat field, the second extension contains the variance image, and the third extension contains a bitwise set mask that flags pixels identified as bad and pixels that were generated from saturated pixels (see §2.9 for more information about the flags).

The wavelength calibration file contains four extensions as well. The zeroth extension contains a normal FITS header, the first extension contains an image where each pixel is set to its wavelength (*in vacuo*), the second extension contains an image where each pixel is set to its spatial coordinate in the slit, and the third extension contains a bitwise set mask that identifies pixels that identified bad pixels and pixels that were generated from saturated pixels.

Note: PDF files showing the lines that are used to determine the wavelength solutions for the various modes can be found in `Spextool/instruments/uspex/data/` or `Spextool/instruments/spex/data/`.

Note: The scattered light is not removed in the process of constructing the flats. However, the scattered light levels in flat frames produced by the pre-defined `SpeX cal` macros are extremely small compared to the direct illumination levels in the orders. This has been verified by examining the counts recorded between the orders. In addition, the scattered light is included in the 2-D surface fitting for normalizing the flats.

An example of the quality assurance plot is shown in Figure 3. The upper panel shows the residuals between the fit and the data as a function of column number while the lower panel shows the residuals as a function of order number. Lines in a given order are identified by the same color and outliers in the fit identified by open circles. The RMS of the fit is given at the top of the figure.

Note: Although processing the calibration files typically occurs without error, there are times when problems arise. The most common problem is when not enough lines are identified which causes the fit to produce spurious results. In this case, `Spextool` will present a warning to the user.

3.3.2 Sky Frames

5. If the user has acquired data by moving the objects between two positions on the slit (i.e., the pair mode), or if the user does not wish to subtract a sky frame, this step is unnecessary and

the user can skip to §3.4. However, if the user acquired data by nodding to sky between object frames, then a “Super sky” frame can be created and subtracted from the object frames. Click on the **Combine Images** button in the middle of the Spextool GUI. Select the **A** beam switching mode. Type in the numbers of the files you will use to make a sky frame (e.g., 21, 23, 25, 27, 29). Remember to change the File Prefix in the File Read panel if the prefix is different from that used for your object images.)

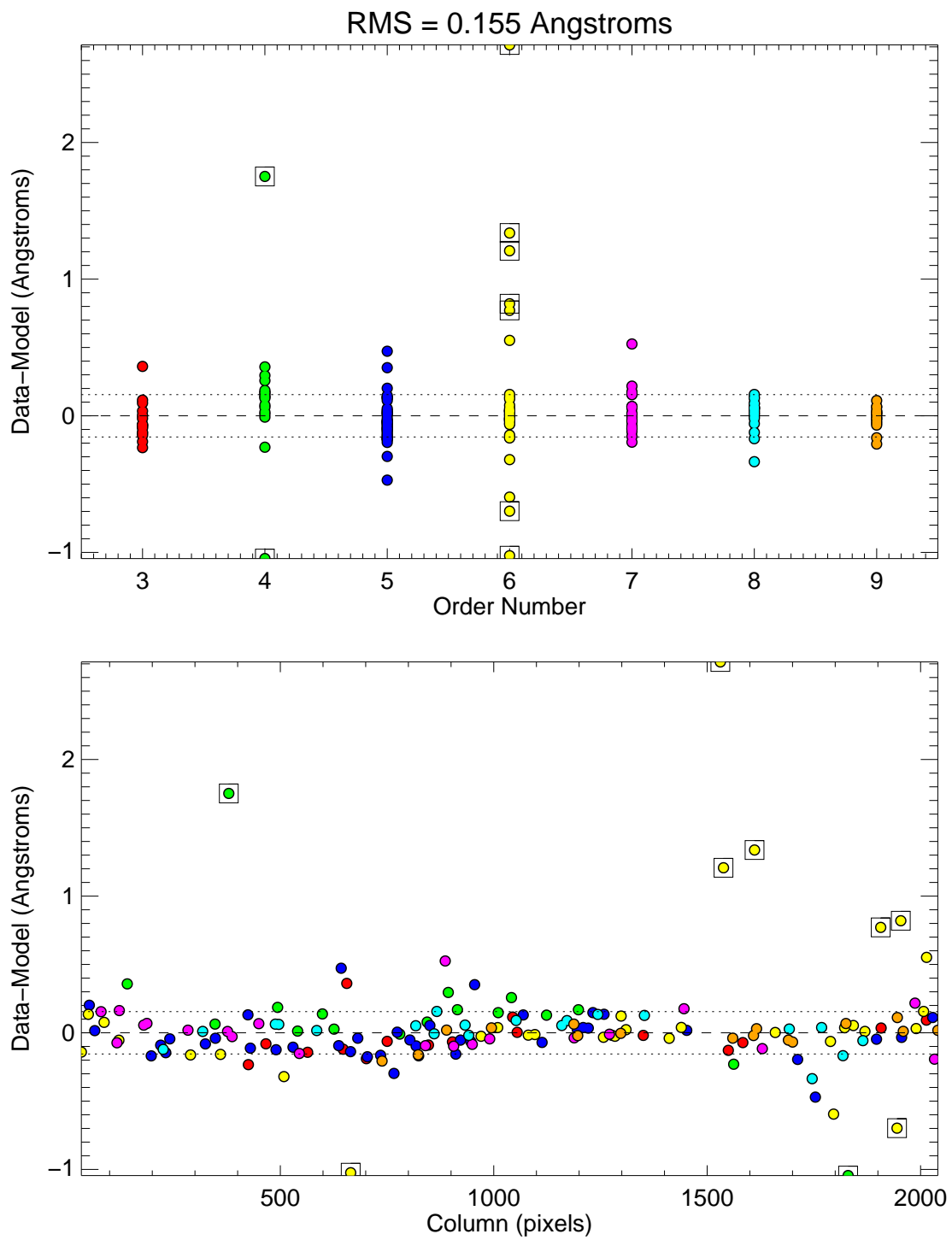


Figure 3: A quality assurance plot for the wavelength calibration.

6. If the user wishes, the sky frames can be scaled to a common flux level on an order-by-order basis. To do so, select **Scale Orders** and give the full name of the normalized flat field created above in the **Full Flat Name** field. The users should then choose which statistic will be used to combine the sky frames. §2.8 gives a summary of each statistic. Finally, select the **cal/** directory, give the name of the output file (e.g. sky21-29) in the **Output Name** field and click **Combine Images**. The sky frames will be combined and a multi-extension FITS file will be written to **cal/** directory. The zeroth extension contains the FITS header, the first extension contains the sky image, and the second extension contains the variance image.

***Note:** The images will not actually be flat-fielded. Rather, Spextool requires information stored in the flat field header to locate the orders.*

3.4 Extraction of Bright Objects

3.4.1 Loading the Data

7. Prepare for extraction of your spectra by clicking either the **Point Source** or **Extended Source** button in the middle of the GUI. This will bring up a set of panels for the chosen source type. For the illustrative purposes of this manual, we will assume the observed objects are point sources.
8. The user should select the **File Readmode** (see §2.7). The default mode of **Index** is by far the most common and therefore the user should also select the prefix of the filenames that will be reduced, either by typing it into the field or selecting it from the **Input Prefix** pulldown menu.
9. In the Reduction Mode panel, to the right of the File Read Mode panel, select the type of observing mode used to acquire the data. If you do not wish to do any sky subtraction at all, choose **A**. If you created a master sky frame in §3.3.2, choose **A-Sky**, and enter the full name of the sky frame in the **Full Sky Image** field. If the data were acquired in the standard infrared method of moving the object between two positions on the slit (the "pair" method), or if the B frames are sky frames for an extended source, choose **A-B**.
10. If the Reduction Mode is **A-B**, type in the numbers of the first two object frames (in the case of the SXD test data, the numbers would be 1, 2) in the **Images** field, give the full name of the normalized flat field in the **Full Flat Name** field (e.g., flat17-21.fits), and give the full name of the Wavecal file in the **Full Wavecal Name** field.(e.g., wavecal22-22.fits).

***Note #1:** The directory button next to the **Images** field which contains the choices, *raw/*, *cal/*, and *proc/* defaults to *raw/*. However, in principle the user can extract from images in either the *cal/* or *proc/* directory, e.g, see §3.5.*

Note #2: *If the user selected the A mode, then he/she should enter a single frame number into the Images field, e.g. 1.*

Click the **Load Image** button. Spextool will apply linearity corrections to the images, then subtract the pair of images and divide the result by the normalized flat field. The flux, uncertainty, S/N, wavelength calibration and spatial calibration images will be displayed in `ximgtool`. The user can scroll through the buffers by clicking ‘f’ for **F**orward and ‘b’ for **B**ackwards.

Note: *If the user does not want to divide by the normalized flat field, then he/she should turn off the flat fielding in the **Other** panel. The flat field image is still required, however, because its FITS header contains information necessary for extraction process.*

Pixels in either the A or B frame that have values above 35,000 DN are colored red in the `ximgtool`. SpeX observers are strongly advised never to allow the counts in a single image to exceed 35,000 DN, as linearity corrections become highly uncertain above this value.

3.4.2 Create Spatial Profiles and Identify Apertures (Box #1)

11. In the Identify Apertures box (box #1), click on the **Make Spatial Profiles** button. This will construct “average” spatial (i.e., along the slit) profiles in the various orders by performing a median along the wavelength direction at each spatial point. The Point Source version of this procedure automatically attempts to identify and ignore columns of data with little or no source flux; only those columns with significant source flux are used to construct the spatial profiles. The spatial profiles are displayed in a separate window, which can be resized to see the results.
12. If the user wishes to define extraction apertures based on the spatial profiles (which is normally the case), s/he should click on the **Manual** button. In some cases, the user does not want to specify apertures defined from the observed profiles, but rather wishes to extract spectra corresponding to apertures which have been previously defined based on observations of another object (e.g., a standard star).
 - **Manual Aperture Definition:** If the stellar peaks are clearly discernible, select the **Auto** button and then the number of apertures to be found. For typical spectra obtained in pair, or A-B, mode, there will be two apertures, corresponding to the object in the A frame and its negative counterpart in the B frame. Click on the **Find/Store Aperture Positions** button and Spextool will locate the centers of these peaks automatically, and give the average locations, over all the orders, of the peaks in the **Aps** field. The peak position for each individual profile will be indicated with solid blue lines in the Plot Spatial Profiles window.

If the user has a faint point source for which only a noisy Spatial Profile can be constructed, the **Guess** or **Fix** positions option can be chosen. The approximate positions, *in arcseconds*, along the slit for the centers of the extraction apertures (i.e., the peaks of the profiles) should be given in the **Aps** field. Optionally, the user can move the cursor into the Plot Profile window, type 's' for **Select**, and then choose aperture positions by aligning the red vertical line of the cursor at the desired location and clicking with the left-most mouse button. A dashed blue line will appear in order to denote the selected aperture position. The user can continue choosing aperture positions with the mouse button, or can start over by typing 's' again.

- **Stored Aperture Positions:** In this case, the user should click the **Import Coeffs** button rather than the **Manual** button. The file containing the trace of the previously extracted object should be entered in the **Trace File** field (see §3.4.4 to see how to create a Trace File).

Click on the **Find/Store Aperture Positions** button and Spextool will locate the centers of these profiles. If **Guess** is selected, Spextool will use these aperture positions as initial guesses to locate the centers of the profiles. In this case, as with **Auto**, the centers of the profile peaks (i.e., the average peak positions in arcseconds for all the orders) found by Spextool will be automatically updated (or entered) in the **Aps** field in the Find Apertures panel and the new positions will be shown with solid blue lines in the Plot Profiles window. If **Fix** is selected, the location of the apertures as specified by the user will be adopted and will not be modified in the **Aps** field or on the Plot Profiles window; the dashed blue lines will become solid blue lines at the specified locations of the aperture position centers.

If Spextool has difficulty locating peaks in the Spatial Profiles in some orders, the user may specify aperture positions on an order-by-order basis. At the top left of the Plot Spatial Profiles window, the user can choose the **Per Order**, instead of the default **All Orders**, selection. The user should then type 's' and s/he will then be able to specify aperture positions in each order by moving the cursor over the order and clicking the left-most mouse button at the desired position. When the user is finished selecting aperture positions, s/he should click on the **Find/Store Ap Positions** button in the main Spextool GUI. Spextool will either attempt to find the profile peaks for the aperture centers (if **Guess** is selected) or adopt the specified locations (if **Fix** is selected). The mean aperture positions for all the orders will be given in the **Aps** field.

If the user observed an extended object, the positions, *in arcseconds*, along the slit of each aperture to be extracted can be entered in the **Aps** field. Optionally, the user can move the cursor into the profile plot panel, type 's', and then choose an aperture position by clicking with the left-most mouse button. A dashed blue line will appear to denote the selected aperture position. The user can continue choosing aperture positions with the mouse button, or can start over by typing 's' again. Click on the **Find/Store Aperture Positions** button and Spextool will store the specified positions. At this point, the dashed blue lines will become solid blue lines at the locations of the apertures. The method of specifying and finding apertures for extended objects is identical to that used for point sources when the **Fix** option is

selected (see description above).

Note: Differential atmospheric refraction will cause the peaks in the Spatial Profiles to be located at slightly different positions (in arcseconds) along the slit in the various orders. This is automatically corrected for in the Point Source mode because Spextool finds the peaks in each order independently. However, it is not corrected for in the Extended Source mode. The user should keep this in mind when specifying aperture positions in the Extended Source mode. This problem can be eliminated to some extent by specifying the aperture positions in each order separately using the Per Order option described above.

3.4.3 Choose Orders (Box #2)

13. Choose the spectral orders to be extracted in The **Choose Orders** box (box #2). Normally the observer will want all spectral orders. However, if an order contains so little flux that the spectrum cannot be traced, the user should de-select (un-click) that order. The wavelengths covered by each order are given in Tables 5 and 1.

3.4.4 Trace Objects (Box #3)

14. The user has two options to trace the position of the source on the array. For extremely faint sources where it is unlikely that a proper trace can be computed, the user can simply use the aperture positions generated in §3.4.2 by clicking the **Use Ap Positions** button. Otherwise, Spextool will attempt to trace the centers of the apertures. If the extraction apertures haven't been fixed by the user, Spextool will fit a Gaussian to the spatial profile at every column, using the aperture centers determined above as the initial guess. The centers of the Gaussians are then fit with a polynomial to derive the trace position as a function of column. If the user has fixed the extraction aperture (e.g., for an extended source or a faint point source), Spextool will simply plot the specified positions on the image and use these as the traces.
15. The coefficients of the fitted polynomial used to trace the location of the object spectrum can be stored in an output file and used later for defining the location of a subsequent spectrum. To do this, the user should enter the root of a file name for the output trace file (e.g., `trace` to create the file `trace.dat`) in the **Filename** field in the Trace Objects subpanel. Otherwise, leave the field blank. The output file can then be used as described in §3.4.2 above.
16. Now click on the **Trace Objects** button in the Trace Objects box (box #3).

3.4.5 Define Extraction Parameters (Box #4)

17. The extraction apertures can now be defined in the **Define Extraction Parameters** box (box #4). The point source and extended source extraction parameters are different so we discuss

each separately below.

Point Source

In Point Source mode, Spextool carries out a weighted profile (or “optimal”) extraction as the default extraction method. (Optimal extraction cannot be performed on extended sources and Spextool has no capability for optimal extraction in Extended Source mode.) Weighted profile extraction requires a radius value over which the source profile is defined. This is the **PSF Radius** value found at the top of the **Define Extraction Parameters** box. The **PSF Radius** value should be set to the radius value *in arcseconds* which contains all the flux from the source - that is, at which the spatial profile of the source drops to zero flux. This value will vary from source to source depending on the seeing conditions at the time of the observations. For the typical seeing at the IRTF, a typical value might be in the range of 2.0 – 2.5 arcseconds.

Note that the **PSF Radius** is a critical parameter for proper flux calibration of spectra reduced with the optimal extraction mode of Spextool, as Spextool will normalize the Spatial Profile to unity within the PSF Radius. For a description of optimal extraction, please see, [Horne \(1986, PASP, 98, 609\)](#). If the user does not wish to perform an optimal extraction, s/he should de-select **Optimal** button at the top **Define Extraction Parameters** box. The **PSF Radius** field will be grayed out.

For either optimal or non-optimal extraction, the user must choose the value of the radius of the extraction aperture (**Ap Radius**) *in arcseconds*, based on the spatial profiles created in §3.4.2. The **Ap Radius** is the size of the aperture that Spextool uses to compute the source flux at each column. If optimal extraction is being performed, the **Ap Radius** can be as large as the **PSF Radius**, but no larger; in this case, Spextool will compute an estimate of the source flux from the weighted mean of the values derived from the pixels within the **Ap Radius** size. For non-optimal extraction, Spextool will simply sum the source flux from the pixels within the **Ap Radius**.

If non-optimal extraction is being performed, the user must choose whether or not to subtract any background. (There is no subtraction option if optimal extraction is chosen: the background level must be subtracted.) If background subtraction is desired, click the background subtraction button (**BG Sub on**). (This button will be automatically selected in the Optimal Extraction mode, where background subtraction is required.)

In the case of background subtraction, the user must give the start radius, *in arcseconds*, for the background window, and the width of this background window *in arcseconds*. The start radius for the background window must be larger than the **PSF Radius** (in optimal extraction mode) or the **Ap Radius** (in non-optimal extraction mode). Specify the degree of the polynomial used to fit the background in these windows and across the object aperture in the **Fit Degree** field. Degree = 0 is a constant; Degree = 1 is a linear fit with slope and offset.

Note: Sometimes the data have such low S/N that the spatial profiles fail to adequately model the shape of the PSF. In this case, the user can select **Median Profile** and Spextool

will use a single profile created by computing the median profile over all wavelengths instead of modeling the profile as a function of wavelength.

Extended Source

If the user is extracting a spectrum of an extended object, the radii, *in arcseconds* of each aperture must be entered in the **Ap Radius** field (e.g., 1.5,1.5 for 2 apertures). The radii values should be separated by commas. The positions, also *in arcseconds*, along the slit of the background windows must also be specified in the **BG Reg** field. An example might be 0-2, 13-15. Finally, the user can select the degree of the polynomial that is used to fit the background in the **BG Fit Degree** field.

Note: *that differential atmospheric refraction will cause a fixed position on the extended source to be located at slightly different positions along the slit. This is automatically corrected for in the Point Source mode because Spextool finds the peaks in each order independently. However, it is not corrected for in the Extended Source mode. The user should keep this in mind and make sure the extraction aperture widths are large enough to account for the variation in position of the spectrum with order.*

18. Now click on the **Show Apertures** button. Spextool will show the apertures used for both the background (in red) and the object (in green) on the Spatial Profiles plot and the apertures (in green) in `ximgtool`. If optimal extraction is being performed, the **PSF Radius** value will be marked with a blue vertical dashed line. The **Ap Radius** value will be marked with a green vertical dashed line.

3.4.6 Extract Spectra and Write Spectra to Disk

19. In the **File Read Mode** panel, type in the desired prefix for the output files, if Spextool is in **Index** mode, or the full output file name, if Spextool is in **Filename** mode.

Note: *The .fits extension will automatically be added to filenames by Spextool. That is, if Spextool is in the **Filename** read mode and if the final desired filename is `Jupiter.fits`, then the user should enter `Jupiter` in the **Output File Name** field.*

20. Click **Extract Spectra** and Spextool will extract the spectra and write them to the **proc** directory as FITS files. In the case of the SXD test data, the files would be `spectra00001.fits` and `spectra00002.fits`. The spectra will be displayed in the `xvspec` GUI for inspection. The user can switch between the A and B buffers by either using the **Buffer** pulldown menu or typing 'a' or 'b' in the plot window. The format of the output FITS images is described in §2.10.

3.4.7 Reducing the Rest of the Data

21. The user may now extract *all* of the remaining object spectra and *all* of the standard star spectra with the same extraction parameters by entered the remaining frames into the **Images** field and clicking **Do All Steps**. In the case of the SXD test data, the numbers would be 3–16.

3.5 Extraction of Faint Objects

22. Extracting the spectra of faint objects can be difficult because Spextool may have problems accurately tracing the objects. If Spextool cannot trace the object spectrum in the order(s) of interest on a single pair-subtracted image, the user should combine the 2-D images before extraction to increase the signal-to-noise of the spectrum in the faint order(s). Move to the Combine Images panel by clicking on the **Combine Images** button in the middle of the main GUI.
23. If the data were acquired by moving the object between two positions on the slit (the pair method), choose **A-B** for the **Beam Switching Mode**; if not, choose **A**. Type the image numbers into the Image field, e.g., 1-6.
24. The user can modify the images if they choose before they are combined in two ways:
 - **Scale Orders:** On an order by order basis, the flux values in each order will be scaled to the median of all pixels in that order in all of the images. Typically this would be used for combining dark frames or flat field frames.
 - **Column BG Sub:** The median background level will be subtracted off each column in each order. This effectively is a zeroth order sky subtraction.

In either case, Spextool requires the normalized flat field created in §3.3 so enter the full name of the normalized flat field in the **Full Flat Name** field.

***Note:** The images will not actually be flat-fielded. Rather, Spextool requires information stored in the flat field header to locate the orders.*

25. Choose the statistic that will be used to combine the images. §2.8 gives a summary of each statistic.
26. Finally, select the directory into which the file should be written (we recommend **proc/**) and give the full name of the output file in the **Output Name** field (e.g., `spc1-6`) and click on the **Combine Images** button. Spextool will then combine the images and write the result to disk as a multi-extension FITS file. The zeroth extension will contain the normal FITS header (see §10.1 for an example of the FITS header keywords added by Spextool), the first

extension will contain the combined image, the second extension will contain the variance image, and the third extension will contain the bitwise set flag array.

27. The combined image may now be extracted as described in §3.4. After selecting whether to perform a point or extended source extraction, the **File Read Mode** should be set to **File-name** and the **Reduction Mode** set to **A**. The user can then select the directory where the combined image was written (e.g. **cal/** or **proc/**) and enter the full name of the combined image into the **Images** field. The user can then proceed as normal.

***Note:** Spextool will, however, write both beams (apertures) to a single file. These beams can be combined in `xcombspec` by choosing the **Combine Two Apertures** options (see §4).*

4 Combining Spectra: xcombspec

The `xcombspec` GUI allows the user to combine spectra extracted with `xspextool` into a single spectrum.

4.1 Cursor Commands

- `s` - Select a wavelength range.

4.2 Starting up and Loading the Data

1. In order to load the correct calibration files and programs, `xcombspec` must know what instrument was used to obtain the data. As noted in §3.1, there are two ways to choose the instrument.
2. Typing `xcombspec` at the IDL prompt will launch the `xcombspec` GUI and load the calibration files for the instrument in the file,

```
spextoolpath/data/Spextool_Instruments.dat
```

Alternatively, the user can pass the name of the instrument to `xcombspec` on the command line, e.g.,

```
IDL> xcombspec, 'SpeX'
```

As with `xspextool`, we recommend the user utilize the former method whenever possible. Please check the title bar to make sure the correct instrument is displayed.

3. The user may load data into `xcombspec` in two ways.
 - The most common use of `xcombspec` is to simply combine individual extractions of the standard star and target. In this case, the **Method** should remain **Manual** (the default). The user can either click on the **Path** button and select the path to the spectra to be combined or they can simply type the path into the field.
The user must then specify the manner in which the files are to be read into `xcombspec`. If the files to be combined all have the same prefix, but different numbers (e.g. `spectra00001.fits`, `spectra00002.fits`, `spectra00003.fits`, etc.), then the user should choose **Index** mode (the default). The input prefix must be typed into the **Input Prefix** field (e.g. `spectra`), and the file numbers entered into the **Files** field (e.g., 1–6

in the case of the SXD test science data and 7–16 in the case of the SXD test standard data).

If the files have different prefixes, or if the user simply prefers to select the files interactively, they should choose the **Filename** mode, and specify the file names in the `textbfFiles` field. Alternatively, the files can be selected by clicking on the **Files** button and highlighting the file names from the list that is displayed.

- If the spectra to be combined together are located in different directories, then the user can create a text file with the path to these files. He or she should select **Text File** as the **Method** and then give the path to this text file by either clicking on the **File Name** button or typing the path into the field. This method is most useful if the user wishes to combined fully reduced spectra obtained on different nights.
4. If the input files contain spectra from multiple apertures that are to be combined, the user should select the **Yes** button next to the **Combine Two Apertures** label.

***Note:** The only time that the user is required to change from the default **No** is if he/she combined the two-dimensional data of a (most likely faint) point source observed in A-B mode before extracting the spectra as described in §3.5. If the files to be combined were extracted individually as described in §3.4, then input files will not contain multiple apertures and the user should select **No**.*

5. Click on the **Load Spectra** button to load the files. The spectra will then be displayed in the display panel on the right hand side of the GUI. If the data files contain multiple orders, all of the orders will be displayed. The user has the choice of displaying the fluxes, the uncertainties, or the S/N ratios as a function of wavelength, by choosing from the **Type** pull down menu above the panel. The different apertures (if available) can also be viewed by selecting the aperture from the **Aperture** pull down menu in the upper left hand corner. Finally, the user can see what the combined spectra will look like by select **Combined** in the **Plot** pull down menu instead of **Raw**.

4.3 Modifying the Spectra: Scale, Prune, Correct Shape

At this point, the spectra are ready to be combined. However, there are typically several modifications to the spectra that should be performed before doing so. As a result of variable slit losses, the average flux levels of each spectrum are different, and thus as seen in the `xcombspec` window, the spectra appear to fan out. This can be corrected by scaling the spectra to a common flux level as described in §4.3.1. A second order correction to the flux levels is often required because we see a heterochromatic (i.e. wavelength dependent) component to these slit losses that affects the overall shape of the spectra. This correction is described in §4.3.3. The scale and shape corrections are particularly important if the user is going to use the dispersion of flux values at a given wavelength

as a measure of the uncertainty in the flux density at that wavelength (see §2.8 for a more in depth discussion of this issue).

A final modification that is seldom needed is to prune sections of spectra or an entire spectrum. This may be necessary if many of the spectra have a similar defect, e.g. a cluster of bad pixels, such that the robust sigma clipping cannot remove the bad pixels or if a single spectrum shows clear deviations from the rest. These modifications are described in §4.3.2.

***Note:** Although the **Prune Spectra** button appears before the **Correct Spectral Shape** button, it can be used after correcting the spectral shape..*

At any point in the process, the user can see the result of combining the spectra by selecting the **Combined** option from the **Plot** pull down menu at the top of the plot window. One can also see the S/N spectrum for the combined spectrum by choosing **SNR** from the **Type** pull down menu at the top of the plot window. If the user wishes to simply combine the spectra, then he/she can skip to §4.4.

4.3.1 Scaling the Spectra

6. The purpose of combining spectra is to increase the S/N of the source spectrum by averaging out the fluctuations due to noise. However as noted previously, as a result of guiding errors, variable sky transmission, etc., rarely will it be the case that all of the individual spectra in a given order have the same flux level. If the final uncertainty on a flux density value in the combined spectrum is computed using some form of the standard deviation of the input flux density values, then directly combining spectra with different flux levels can defeat the purpose of the combining process, by increasing, rather than decreasing, the noise.

`Xcombspec` determines a *single* scale factor that is applied to all orders of a given spectrum². That is, the factor determined for spectrum 2 in order 5 is also applied to the corresponding spectrum 2 in order 3. Therefore, we suggest that the scale factors should generally be determined from the middle orders (e.g., 5 in SXD mode), unless the user has a particular reason for choosing another order. (For example, if no flux is detected in the higher orders, 7 and 8, it might be better to use order 4 to determine the scale factor.) We also recommend choosing an order with a high overall S/N value. For example, for the SXD mode, orders 5 or 6 are generally the best to determine the scale factors. In Box #2, the user should choose the order with which the scaling should be determined from the **Order:** pulldown menu, click **Scale Spectra** and the `xscalespec` GUI will appear.

7. By default, the spectra will be scaled to the median of the set of spectra using the wavelength range denoted by the dotted cyan lines. If the user would like to change the wavelength range, type 's' (for **Sselect**) and click with the left most mouse button to specify the short

²The reason for this choice is discussed in more detail in §11.

wavelength limit of the selected range. Click again with the left most button to specify the long wavelength limit. The user can also choose to scale the spectra to one of the spectra instead of the median spectrum. To do so, select **Spectrum** from the **Scale to:** pull down menu in the upper left of the plot window and then the number of the desired reference spectrum should be chosen from the other pull down menu. `Xcombspec` will then determine the scale factors to be applied to each spectrum, and will scale them appropriately. If **None** is chosen at any point in this process, the original unscaled spectra will be re-plotted. We recommend using the **Median** for the scaling.

8. Once the user is satisfied with the scaling, s/he should click on the **Accept** button. At this point, the plot GUI will disappear, and the scale factors determined above for each spectrum will be applied to all the spectra in all the orders. If the results are not acceptable, the scaling can be re-determined by choosing a new scaling order, a new reference spectrum, a different wavelength range, or the spectra can be re-loaded and the process repeated from the beginning.
9. Ideally, by scaling all spectra in every order to a common value all the spectra should now lie perfectly on top of one another. However, we have found that this is not the case. After scaling, often the spectra in orders farthest from that used to determine the scale factor exhibit a large dispersion about the mean. This implies that the spectral slope is varying from one spectrum to another over the various orders. One can see this change in spectral slope even across a single order if the spectra are examined closely. We believe this slope change is the result of guiding errors, atmospheric dispersion, and time-variable, wavelength-dependent changes in seeing. Based on our tests, we do not believe it is due to any procedures carried out by Spextool during the data reduction. The user can correct for this dispersion in §4.3.3.

4.3.2 Pruning the Spectra

10. The user can both remove spectra from an order and/or mask out parts of a spectrum before they are combined. To do so, the user should select **Prune** from the **Modify Spectra** pull down menu and then select an order from the **Order:** pull down menu and the `maskspec` GUI will appear.
11. At any time the user can control which spectra are displayed by **Plot** from the pull down menu and then selecting which orders to display. At any time, the user can select **All** and all of the spectra will be displayed or **None** and none of the spectra will be displayed.
12. If the user would like to remove an entire spectrum, he/she should select **Remove** from the pull down menu and select which spectra to remove. The **All** button is grayed out because at least one spectrum must be present. However, the user can click the **None** button at any time and all the spectra will be displayed.
13. If the user would like to mask parts of a spectrum, he/she should select **Mask** from the pull down menu and then select which spectra will be masked. The user can choose the wave-

length range to mask by typing 's' (for **Select**) and then left-clicking the mouse button on the left and right wavelength limits. To **Undo** **all** of the masks, type 'u'.

***Note:** Once the user modifies which spectra are to be masked, they can no longer undo any previously generated masks.*

14. When the user is satisfied with the selection of spectra to remove and the regions to be masked, he/she should click the **Accept** button at the bottom of the GUI.

4.3.3 Correcting the Shape of the Spectra

15. The user may choose to reduce the dispersion in the spectra about the mean (and therefore increase the S/N of the final combined spectrum) by correcting for these slope variations. This can be done by clicking on the **Correct Spectral Shape** in box #2. In each spectrum **xcombspec** will then remove the low order variations, relative to the reference spectrum, from each spectrum, order by order. After this has been done, all the spectra in a given order should lie on top of one another, which will then increase the S/N in the resulting combined spectrum.

***Note:** The results of the Correction should be inspected carefully. While we have set the parameters of the procedure such that it should work in most cases, it can sometimes generate obviously spurious results. This is particularly true if the input spectra have very low S/N. If the user is uncertain about the results, do not perform the shape correction.*

The **Correct Spectral Shape** step cannot be undone. If the user wishes to undo this correction, s/he will have to re-load the spectra and start the combining procedure from the beginning.

4.4 Combining the Spectra

16. The user should now choose the statistic to be used for the combining procedure. §2.8 describes each statistic.

4.5 Write the File to Disk

17. Give the root of the output file name in the **File Name** field in Box #4 (e.g. `cspectral-6` for the SXD test science data) and click on the **Write File** button (the .fits suffix will be automatically appended to the root). The final combined spectrum will be displayed in the

`xvspec` GUI. The FITS file has the same format as the Spextool FITS files described in §3.4.6. Please see §10.2 for an example of the FITS header keywords added by Spextool at this step of the reduction.

5 Telluric Correction and Flux Calibration: `xtellcor`

`xtellcor` is the telluric correction program written by Bill Vacca and Mike Cushing for use with SpeX. Users can find a description of the code in the paper by [Vacca, Cushing, & Rayner \(2003, PASP, 115, 389\)](#) and we would ask all users to reference this paper if they use `xtellcor`.

`xtellcor` uses observations of A0 V standard and a high resolution model of Vega to remove both telluric absorption and the instrument throughput. In brief,

$$F_{\text{obj}}^{\text{intr}}(\lambda) = F_{\text{obj}}^{\text{obs}}(\lambda) \left(\frac{F_{\text{vega}}^{\text{mod}}(\lambda)}{F_{\text{A0 V}}^{\text{obs}}(\lambda)} \right) \quad (4)$$

where $F_{\text{obj}}^{\text{intr}}(\lambda)$ is the intrinsic spectrum of the source, $F_{\text{obj}}^{\text{obs}}(\lambda)$ is the observed spectrum of the source, $F_{\text{vega}}^{\text{mod}}(\lambda)$ is a model spectrum of Vega modified to match the radial velocity, reddening, resolving power, and H I equivalent widths of the A0 V standard star, and $F_{\text{A0 V}}^{\text{obs}}(\lambda)$ is the observed spectrum of the A0 V standard star. Most of the steps in the `xtellcor` GUI are aimed at properly modifying the Vega model.

Three additional programs associated with `xtellcor` are `xtellcor_finish`, `xtellcor_basic` and `xtellcor_general`. `xtellcor_finish` allows the user to apply previously generated telluric correction spectra to data, `xtellcor_basic` allows the user to divide by a standard star (and optionally multiple by a Planck function) which can be useful for solar system observations, and `xtellcor_general` is a general version of the code for use with other instruments. The first two routines are described in more detail in Sections 5.3 and 5.4 while the latter routine is described in its own user manual which can be found in the directory `Spextool/manuals/` of the `Spextool` package.

5.1 Cursor commands

The following cursor commands are used in various subroutines described below.

- **e** - to **E**stimate the scale factors in the `xscalelines` GUI
- **f** - to **F**ix a region of the telluric spectrum in the `xscalelines` GUI
Press and release the left mouse button on the left and right side of the bad region. The bad region is replaced using the edge pixels to define a line. Type ‘u’ to **U**ndo the edit.
- **m** - to **M**odify the boundaries of a selected continuum region in the `xconkern` GUI
- **n** - cursor enters **N**ormalization mode in the `xconkern` GUI
Select continuum regions to normalize the spectrum by clicking the left mouse button on the left and right sides of the region.

- s - to **S**elect a wavelength region in the `xconkern` and `xfindshift` GUIs
- u - to **U**ndo a **F**ix in `xscaleines`

5.2 xtellcor

5.2.1 Starting up and Loading the Data

1. Typing `xtellcor` at the IDL prompt will launch the `xtellcor` GUI and load the calibration files for the instrument in the file,

```
spextoolpath/data/Spextool_Instruments.dat
```

Alternatively, the user can pass the name of the instrument to `xtellcor` on the command line, e.g.,

```
IDL> xtellcor, 'uSpeX'
```

As with `xspextool`, and `xcombspec` we recommend the user utilize the former method whenever possible. Please check the title bar to make sure the correct instrument is displayed. The `xtellcor` GUI, which is divided into five sections corresponding to the steps to be carried out in performing the telluric correction.

2. Enter the fullpath of the standard star file in the **Std Spectra** field.

Note: The standard star file must contain only a single aperture. If the standard star was extracted from a set of combined images, then the two apertures must first be combined using `xcombspec` (select combine apertures in Box 1 of the GUI).

3. Enter the *B*- and *V*-band magnitudes in the **Std Mag (B,V)** fields. If the magnitudes are unknown, the user can enter the same magnitude (any number) for B and V. In this case, the pseudo flux calibration will not be correct.
4. Enter the fullpath of the object spectra in the **Obj Spectra** field.
5. Click the **Load Spectra** button to load the spectra into memory. Note that the airmass values for both spectra and the airmass difference will appear at the top of the `Xtellcor` panel. The panel is colored coded such that it is green if the absolute value of the airmass difference is less than 0.1 and red if it is greater than 0.1. Typically airmass differences of greater than 0.1 result in spectra that are poorly corrected at wavelengths with strong telluric absorption.

5.2.2 Deriving the Kernel

The next step involves generating a convolution kernel that will be applied to a (stored) model spectrum of Vega. The kernel will be convolved with the Vega model spectrum (which will then be scaled to the observed magnitudes of the A0V star) in order to simulate the observed spectrum of the A0V standard star at the resolution of the SpeX data. The division of the observed stellar spectrum by the convolved and scaled Vega spectrum will then yield the telluric correction spectrum that will be applied to the object spectrum.

There are two methods available to generate the kernel. The first involves creating the kernel based on the observed spectrum of the standard star (**Deconvolution Method**). The second method generates a kernel from the profile of the arc lines (**IP Method**). The Deconvolution method is recommended for reducing SXD spectra. The IP method must be used when correcting LowRes15 observations and is recommended for LXD data.

Deconvolution Method

6. If the user is building the convolution kernel from the spectra of the observed A0V standard star, s/he should select **Deconvolution** as the Method in Box 2. Then choose an order from the pull down menu. The selected order should contain a H absorption line in the spectrum of the A0V standard star that is *unaffected* by telluric absorption and has high S/N. The Paschen δ line at 1.005 microns has been found to have minimal contamination by telluric features at the resolution of SpeX data. This is in order 6 in the SXD mode. We have also obtained very satisfactory results using the Br γ and Br α lines when reducing LXD spectra. These are in orders 9 and 5, respectively, of LXD data.
7. Click on the **Construct Kernel** button. The **Xconkern** GUI will appear and the spectrum of the A0 V star in the chosen order will be plotted in the upper half. A atmospheric transmission curve at the resolving power of the data is also shown in yellow. The user now must normalize the stellar spectrum by selecting “continuum” regions from the data and fitting them with a polynomial. Successful kernels can be generated by normalizing either the entire order spectrum (as shown in the Vacca, Cushing, & Rayner (2003, PASP, 115, 389) article) or by expanding the region around the chosen H line (with the “z” cursor command - see and normalizing the continuum only around that line.
8. Select the **Raw** button for the choice of Plot Type at the top of the Xconkern panel. Typing ‘n’ will put the user into the “Normalization mode”. Spectral regions representing continuum that are to be fitted by the program can then be chosen by clicking twice with the left-most mouse button, once for the short wavelength limit of the region and once for the long wavelength limit. The region thus selected will be designated with dashed cyan vertical lines. The boundaries of a region can be shifted in wavelength by typing “m” (for **M**odify) and dragging the cyan line leftward or rightward by clicking on the left-most mouse button and keeping it held down while moving the mouse. The user can continue in this manner to select any number of normalization regions. If s/he wishes to erase all regions and start the

selection process over again, s/he can do so by clicking on the "Clear" button at the top right of the window.

9. Once all desired continuum fitting regions have been selected, choose the degree of the polynomial fit using the pull down menu at the top of the Xconcern panel. (Degrees of 6-9 seems to work well to normalize the entire spectrum of an A0 V star in order 6.) Then click on the **Fit Continuum** button. The polynomial fitted to the continuum regions will be overplotted on the spectrum.
10. Once a good fit to the continuum is achieved, select the **Normalized** button at the top of the Xconcern panel. This will display the normalized spectrum of the standard star.
11. The user now must select a wavelength region containing an absorption line that will be used to construct a kernel. This is done by typing 's' (for **Select**) and clicking with the left-most mouse button on the short and long wavelengths bracketing the absorption line. For the Pa δ line, low and high wavelength limits of approximately 1.000 and 1.010 microns have been found to work reasonably well. Then click on the **Construct Kernel** button in the middle of the panel.
12. The program then generates a convolution kernel using the method described in the [Vacca, Cushing, & Rayner \(2003, PASP, 115, 389\)](#) paper. It then convolves this kernel with the model spectrum of Vega and divides the observed spectrum of the standard A0 V star by this convolved Vega spectrum. The observed spectrum of the standard star, the the original Vega spectrum (binned to the sampling of the A0 V star), the convolved Vega spectrum, and the result of the division ("residuals") are displayed in the bottom window of the Xconcern panel. Experience has shown that it is fairly easy to obtain residuals with maximum deviations of less than about 2%, and RMS deviations less than about 1% about the Pa δ line in good S/N standard star spectra.
13. The user can continue with steps 8-12 until s/he is satisfied with the residuals of the convolution. The s/he should click on the **Accept** button. Xtellcor will then convolve the Vega model with the kernel and scale the model to the observed A0V magnitudes. The division of the observed A0V spectrum by this scaled and convolved Vega spectrum generates the "Telluric Correction Spectrum".

IP Method

14. If the user is building the convolution kernel from the shape of the arc lines, s/he should select the "IP" (for "Instrument Profile") button and simply click on the "Construct Kernel" button in section 2 of the Xtellcor control panel. The IP method is recommended for reducing LowRes spectra and any LXD spectra for which the observed A0V spectrum contains no suitable (high S/N) H lines.

5.2.3 Constructing the Telluric Spectrum

15. The user can now make adjustments to account for the fact that the observed A0 V star may not have the same strengths of the Hydrogen lines as in the Vega model spectrum. Click on the **Scale Lines** in Box 3 and the `xscalelines` panel will appear.

In the bottom window of the panel is the estimate of the telluric spectrum (in white) and the atmospheric transmission at the resolving power of the data (in yellow). The telluric spectrum, or the result of applying this telluric to the object spectrum, can be viewed by selecting either the **Telluric** or **Object** button in the middle of the GUI. The positions of the Hydrogen lines present in A0 V stars are labeled and marked in green.

Ideally, the telluric spectrum should look similar to the typical atmospheric absorption spectrum times the instrument throughput (which is a smoothly varying function). However, because the Equivalent Widths of the H lines in the observed star do not necessarily match those in the model spectrum of Vega, broad “emission” or “absorption” features may appear in the telluric spectrum at the wavelengths of the H lines. `Xscalelines` provides a method of scaling the model equivalent widths in order to remove these features from the telluric spectrum.

In the upper panel is a plot of the initial scale factors used by the program to scale the H line Equivalent Widths in the model spectrum. If the user constructed the kernel with the Deconvolution Method, all the scales will be set to the ratio of the equivalent width in the observed spectrum to the equivalent width in the model spectrum. If the user constructed the kernel with the IP Method, all scales will be set to unity.

16. The goal of this step is to remove the stellar H lines from the telluric spectrum and generate a telluric correction spectrum that contains only those features due to atmospheric absorption. The typical telluric spectrum shown in yellow should give the user an idea of where the true atmospheric features are, what their approximate relative strengths should be after removal of the stellar H lines, and how much the H lines in the (white) telluric spectrum should be scaled. To scale the strengths of the H lines, the user can zoom in on a region around any stellar H line in the bottom panel with the ‘z’ command. If the line is fairly isolated and has continuum regions on either side of it, the user can type ‘e’ (for **E**stimate) and click the left-most mouse button twice, once on each side of the feature in the continuum regions. `xscalelines` will automatically attempt to compute the best scale factor for that particular line based on a fit of a background+gaussian profile to the region in the telluric spectrum selected with the ‘e’ command (we do not recommend use ‘e’ on the H lines in LowRes15 spectra, see below). The scale factors can also be adjusted by hand by clicking on the green points in the upper window with the left-most mouse button, holding the button down, and dragging the point up or down.

If the user finds that s/he is unable to satisfactorily remove the the stellar H line from the telluric correction spectrum, s/he has the option of linearly interpolating over any remaining residual features. This option can also be used if the star used as a telluric standard is found to have emission - rather than absorption - at some of the H transitions. Type ‘f’ (for **F**ix)

and then click the left mouse button on the left and then right side of the residual feature. The residual feature will be interpolated over using the flux values at the wavelengths chosen by the user. To undo the interpolation, type 'u' (for **Undo**).

Note: *The interpolation feature should be used with caution since any atmospheric features present will also be removed from the telluric correction spectrum. We recommend restricting the use of this option to only those regions and features where the typical atmospheric spectrum is seen to be very smooth (e.g. in order 8 of the SXD mode).*

Whenever the scale factors are adjusted (either by using the 'e' or 'f' commands or by dragging them by the user by hand), `xscalelines` will fit a spline through all the scale factors at each H line and use the new array of scale factors to recompute a new telluric spectrum. The telluric-corrected object spectrum can be examined at any stage by selecting the "Object" button at the top of the lower window. This will show the user what the effects of changing the scale factors are on the object spectrum. However, we do not recommend that users base their scale factor adjustments on the results seen in the Object spectrum! The scale factors should be adjusted based on the generation of a telluric spectrum that approximates the typical atmospheric curve.

17. Examine the telluric spectrum in each order (by selecting the order from the **Order** pull-down menu in the middle of the Xscalelines panel) and correct as many features as necessary using the method described above. Typically, orders 7 and 8 in the SXD mode require the most corrections, and often they require the interpolation option described above.

Note that for some features it may not be possible to remove the residuals completely. This is particularly the case when using the IP mode. In some cases it may be necessary to shift the Vega model spectrum relative to the observed spectrum in order to decrease the size of the residuals. (A relative velocity offset is computed in the "Deconvolution" method, but not when the "IP" method is used.) The user can enter a relative velocity in the "Vshift" field at the top of the Xscalelines window. The Vega model used to construct the telluric correction spectrum is then shifted and a new telluric correction spectrum is generated. Note that the velocity shift is applied to all orders simultaneously. It is not possible to apply different velocity shifts to different orders.

18. When the user is satisfied with the telluric spectrum in each order, s/he should click on the **Accept** button at the bottom of the `xscalelines` GUI.
19. When all orders have been inspected and the line scaling has been finished, the user can select the units desired for the output telluric-corrected object spectrum from the **Units** pull-down menu. Then click on the **Construct Telluric Spectrum** button. The program will then construct the telluric spectrum for each order by dividing the observed A0V standard star spectrum by the convolved and scaled Vega model whose H line EWs have been adjusted as described in steps 18-19.

5.2.4 Determining Residual Wavelength Shifts

We often find there are slight wavelength shifts between the A0 V star used to construct the telluric spectrum and the object to be corrected. These shifts need to be removed in order to avoid introducing spurious noise and artifacts when dividing the object spectrum by the telluric spectrum.

***Note:** This step is optional and can be skipped if the user so desires.*

20. To estimate the wavelength shift for a given spectrum and correct for it, choose an Aperture and an Order from the pull-down menus in Box 4. Click on the **Get Shift** button and the `xfindshift` GUI will appear. The object spectrum (white) and the telluric spectrum (green) are both plotted in the upper window along with the atmospheric transmission at the resolving power of the data (yellow). The result of dividing one by the other is shown in the bottom window.
21. Select a region in the top window containing a reasonably strong atmospheric features in both spectra (and preferably one not containing strong absorption or emission features in the object spectrum). This is done by typing 's' (for **Select**) and click with the left-most mouse button on either side of the features. Then click on the **Auto Find** button in the upper left of the window. `xfindshift` will shift the telluric spectrum by fractions of a pixel and search for the best value, corresponding to a minimum in the RMS computed from the telluric corrected spectrum in the selected region. Alternatively, if the user desires a specific shift value (perhaps as the result of determining the shift from another order), s/he can enter the value directly in the **Shift** field and hitting return. Similarly, wavelength shifts can be reset to zero by entering zero in the **Shift** field and hitting return. The user can determine the shift obtained from a different wavelength region by typing 's' and selecting a new wavelength region. When the user is satisfied with the shift found by `xfindshift`, s/he should click on the **Accept** button at the bottom of the window.
22. The user should determine shift values for each order/aperture independently by selecting a new order/aperture in Box 4 and repeating the previous step.

5.2.5 Write the File to Disk

23. Give the root of the output file name in the **File Name** field in Box 5 (the .fits suffix will be automatically appended to the root). The user can also choose to output the telluric correction spectrum as well as the modified Vega model spectrum (shifted to the radial velocity, scaled to the optical mag of the input standard star, convolved with the kernel, and multiplied by the equivalent width scale factor array). Click on the **Write File** button to generate the output files. The spectra will be displayed in the `xvspec` GUI. If the user chose to output the telluric correction spectrum or the modified Vega spectrum, they will be written to disk with

the file names `root_tellspec.fits` and `root_modvega.fits`. Please see §10.3 for an example of the FITS header keywords added by Spextool at this step of the reduction.

5.3 xtellcor_finish

If one observation of an A0V standard is being used to perform telluric corrections for multiple objects, it is not necessary to re-generate the telluric correction curve each time. The user should generate the curve once using `xtellcor`, making sure that the telluric correction spectrum is saved and written out at the end of the process (the default is to do this). For the next object to be corrected, the user should type `xtellcor, /FINISH` at the command line. `Xtellcor_finish` will take the previously generated telluric curve (e.g. `root_tellspec.fits`) and the target object as input. The user will be able to shift the two spectra, as in §5.2.4 and after the best shift is found, `xtellcor_finish` will divide the two spectra and output the corrected object spectrum.

5.4 xtellcor_basic

`Xtellcor_basic` is a GUI that performs basic telluric correction and flux calibration by simply dividing the science observation by a standard star. No attempt is made to remove intrinsic stellar features but the continuum can be restored by multiplying the result by a Planck function of the appropriate temperature. `Xtellcor_basic` can be used to correct observations of solar system objects where the signal is due to reflected sunlight.

5.4.1 Starting up and Loading the Data

1. Type `xtellcor_basic` at the IDL prompt. This will bring up the `xtellcor_basic` GUI, which is divided into four sections corresponding to the steps to be carried out in performing the telluric correction.
2. Enter the fullpath of the standard star file in the **Std Spectra** field.

Note: *The standard star file must contain only a single aperture. If the standard star was extracted from a set of combined images, then the two apertures must first be combined using `xcombspec` (select combine apertures in Box 1 of the GUI).*

3. Enter the fullpath of the object spectra in the **Obj Spectra** field.
4. Click the **Load Spectra** button to load the spectra into memory. Note that the airmass values for both spectra and the airmass difference will appear at the top of the `Xtellcor` panel. The panel is color coded such that it is green if the absolute value of the airmass difference is

less than 0.1 and red if it is greater than 0.1. Typically airmass differences of greater than 0.1 result in spectra that are poorly corrected at wavelengths with strong telluric absorption.

5.4.2 Determining Residual Wavelength Shifts

We often find there are slight wavelength shifts between the standard star used to construct the telluric spectrum and the object to be corrected. These shifts need to be removed in order to avoid introducing spurious noise and artifacts when dividing the object spectrum by the telluric spectrum.

***Note:** This step is optional and can be skipped if the user so desires.*

5. To estimate the wavelength shift for a given spectrum and correct for it, choose an Aperture and an Order from the pull-down menus in Box 2. Click on the **Get Shift** button and the `xfindshift` GUI will appear. The object spectrum (white) and the telluric spectrum (green) are both plotted in the upper window along with the atmospheric transmission at the resolving power of the data (yellow). The result of dividing one by the other is shown in the bottom window.
6. Select a region in the top window containing a reasonably strong atmospheric features in both spectra (and preferably one not containing strong absorption or emission features in the object spectrum). This is done by typing 's' (for select) and click with the left-most mouse button on either side of the features. Then click on the **Auto Find** button in the upper left of the window. `xfindshift` will shift the telluric spectrum by fractions of a pixel and search for the best value, corresponding to a minimum in the RMS computed from the telluric corrected spectrum in the selected region. Alternatively, if the user desires a specific shift value (perhaps as the result of determining the shift from another order), s/he can enter the value directly in the **Shift** field and hitting return. Similarly, wavelength shifts can be reset to zero by entering zero in the **Shift** field and hitting return. The user can determine the shift obtained from a different wavelength region by typing 's' and selecting a new wavelength region. When the user is satisfied with the shift found by `xfindshift`, s/he should click on the **Accept** button at the bottom of the window.
7. The user should determine shift values for each order/aperture independently by selecting a new order/aperture in Box 2 and repeating the previous step.

5.4.3 Restore the Continuum

If the user wishes, they can restore the continuum shape of the spectrum and approximately absolutely flux calibrate the spectrum by multiplying the ratio of the observed object and standard star spectra by a Planck function, e.g,

$$F_{\text{obj}}^{\text{intr}}(\lambda) = F_{\text{obj}}^{\text{obs}}(\lambda) \left(\frac{B(T, \lambda)}{F_{\text{std}}^{\text{obs}}(\lambda)} \right). \quad (5)$$

This implicitly assumes that the star can be modelled accurately as a Planck function. Since this is almost never the case, residuals due to intrinsic stellar lines and differences between the stellar continuum and a Planck function will be present in the final spectrum.

8. If the user does not wish to restore the continuum, s/he should select **No** and move to step 10.
9. The user should enter the temperature of blackbody and the *V*-band magnitude of the standard star. The latter quantity is used to approximately absolutely flux calibrate the final spectrum. Finally, select the units desired for the output telluric-corrected spectrum from the **Units** pulldown menu.

5.4.4 Write the File to Disk

10. Give the root of the output file name in the **File Name** field in Box 5 (the .fits suffix will be automatically appended to the root). The user can also choose to output the telluric correction spectrum as well as the modified Vega model spectrum (shifted to the radial velocity, scaled to the optical mag of the input standard star, convolved with the kernel, and multiplied by the equivalent width scale factor array). Click on the **Write File** button to generate the output files. The spectra will be displayed in the `xvspec` GUI.

6 Merging Orders: xmergeorders

The `xmergeorders` GUI allows the user to merge telluric-corrected orders into a single, continuous spectrum.

6.1 Cursor commands

- `b` - enters the cutting mode for the **B**lue spectrum
- `f` - to toggle between having the blue and green spectrum in **F**ront
- `g` - enters the cutting mode for the **G**reen spectrum
- `l` - changes the cutting direction to the **L**eft
- `r` - changes the cutting direction to the **R**ight
- `u` - to **U**ndo a cut

6.2 Starting Up and Loading the Data

1. Type `xmergeorders` at the IDL prompt which will bring up the `xmergeorders` GUI.
2. In Box 1, click the **Spectra** button and choose the file that contains the spectra to be merged. Alternatively, the user can type the full path of the filename in the field.
3. Select whether to propagate uncertainties during the merging process by either selecting or de-selecting the **Weighted Mean** button. The default is to always propagate uncertainties.
4. Click the **Load Spectrum** button to load the data and the data will be loaded into memory.
5. Select the aperture from which to merge the spectra. In the vast majority of cases, a file will have only one aperture and therefore this step can be skipped.

***Note:** If the file does have multiple apertures, each aperture must be merged and written to disk separately.*

6. In Box 2, select an **Anchor Order** from the pull down menu. The anchor order is the order with which Xmergeorders will start. All other orders will be added to this order (with appropriate scaling factors if desired). Common selections are order 3 for SXD, and the first order of LXD data.

6.3 Adding Orders

7. After choosing an Anchor order, xmergeorders will present a list of neighboring orders that can be merged with the anchor order in the **Add Order** menu in Box 3. For example, if the user is merging SXD data and order 7, xmergeorders will allow the user to choose either order 6 or 8 to be merged with order 7. Select the order to be added. The anchor order and the order to be added will both be plotted in the upper plot. The anchor order will appear in blue, and the order to be added will appear in green. The S/N spectra will appear in the bottom window.
8. The added order can be scaled to match the flux level of the anchor order. Type 's' (for **Select**), and click with the left-most mouse button on the short and then long wavelength boundaries of the region to be used to compute the relative scaling factor. A dotted cyan line will appear after each click at the selected wavelength. When the user clicks on the **Auto Scale** button, xmergeorder will compute the best scale factor for the added order and re-plot the scaled spectrum. The computed scale factor will be shown in the **Scale** field. Alternatively, the user can enter a number in this field and xmergeorders will scale the added order accordingly. To reset the scale, type 1.0 in the scale field and hit return. Note the 's' button will only work if the two spectra overlap. If there is no overlap, (e.g., Orders 3 and 4 of ShortXD) the user can still scale the added order by manually typing the scale factor in the Scale field.

***Note:** The user should avoid using regions of the spectra with low S/N as a spurious scale factor can often be computed. Typically values of the scale factor range from 0.9 to 1.1. If the scale factor is outside this range, then it might be better to simply set the scale factor to unity.*

9. The edges of either the anchor order or the added order can be cut out before the two spectra are merged if the S/N of these regions is low. Type 'g' (or click **Green** for the Trim Spectrum) to trim regions from the green spectrum. Then choose the direction of the cut by typing 'r' or 'l' (or click **Left** or **Right** for the Trim Direction). Clicking with the left-most mouse button removes the spectrum in the desired direction. The blue spectrum can be trimmed in a similar fashion by typing 'b' and then 'r' or 'l'. To undo any cut, type 'u'.

A preview of what Xmergeorders will produce for any two plotted spectra can be seen by selecting the **Combine** button above the main plot window. Selecting the **Overlap** button will show the two separate spectra again. Either spectrum can be temporarily removed from the plot by unchecking the **Blue** or **Green** buttons at the top of the main plot window.

10. When the user is satisfied with the scaling and trimming of the the spectra, s/he should click on the **Merge Orders** button in Box 3. Xmergeorders will then combine the spectra.
11. Repeat steps 7-10 until all the orders have been combined. When the final order has been merged, the complete spectrum will be displayed in xzoomplot.

6.4 Write the File to Disk

12. When all orders have been merged, give the root of the output file name in the **File Name** field (the .fits suffix will be automatically appended to the root) and click on the **Write File** button in Box 4. If the user wishes to append a string to the input file name, s/he can click on the **Copy Input Name** button in Box 4 and the original filename will be copied in the **File Name** field. Please see §10.4 for an example of the FITS header keywords added by Spextool at this step of the reduction.

7 Merging ShortXD and LongXD Spectra: xmergexd

The `xmergexd` GUI allows the user to merge a ShortXD and LongXD spectrum into a single, continuous spectrum.

7.1 Cursor commands

- **b** - Enters the cutting mode for the **B**lue spectrum.
- **f** - To toggle between having the blue and green spectrum in **F**ront.
- **g** - Enters the cutting mode for the **G**reen spectrum.
- **l** - Changes the cutting direction to the **L**eft.
- **r** - Changes the cutting direction to the **R**ight.
- **u** - To **U**ndo a cut.

7.2 Starting Up and Loading the Data

1. Type `xmergexd` at the IDL prompt which will bring up the `xmergexd` GUI.
2. In Box 1, click the **ShortXD** and **LongXD** buttons and choose the files that contains the ShortXD and LongXD spectra to be merged. Alternatively, the user can type the full paths of the filenames in the corresponding fields.
3. Select whether to propagate uncertainties during the merging process by either selecting or de-selecting the **Weighted Mean** button. The default is to always propagate uncertainties.
4. Click the **Load Spectrum** button to load the data and the data will be loaded into memory. The two spectra will be plotted in the top panel while the S/N of the two spectra will be plotted in the lower window.

7.3 Merging the Spectra Together

5. The user can scale and clip the two spectra using the same techniques that were used to merge different orders together as described in §6.3.

7.4 Writing the File Disk

6. When the two spectra have been combined, give the root of the output file name in the **File Name** field (the .fits suffix will be automatically appended to the root) and click on the **Write File** button in Box 4. The spectrum will be displayed in the `xvspec` GUI.

8 Cleaning, Fixing, and Smoothing Spectra: `xcleanspec`

The `xcleanspec` GUI allows the user to 1) clean interpolate over bad pixels, 2) remove regions of the spectrum (e.g. regions with high telluric noise) and 3) smooth the spectra.

8.1 Cursor commands

- f - to **F**ix a region of the spectrum.
- g - enters the cutting mode for the **G**reen spectrum
- l - changes the cutting direction to the **L**eft
- r - changes the cutting direction to the **R**ight
- u - to **U**ndo a cut

8.2 Starting Up and Loading the Data

1. Type `xcleanspec` at the IDL prompt which will bring up the `xmergeorders` GUI.
2. In Box 1, click the **Input Spectrum** button and choose the file that contains the spectrum to be cleaned. Alternatively, the user can type the full path of the filename in the field.
3. Click the **Load Spectrum** button to load the data and the data will be loaded into memory. The spectrum will be plotted in the upper window of the GUI while the S/N of the spectrum will be plotted in the lower window. The user has the option of plotting either the flux density or uncertainty in the upper window by selecting either **Flux** or **Error** in Box 2.

To aid in the identification of potential regions of poor signal-to-noise, the user has the option of overplotting the various hydrogen lines that fall within the wavelength range of the spectrum as well as plotting an atmospheric transmission curve at the appropriate resolving power of the data. In addition, the user can identify pixels that have been flagged by `spextool`.
4. Since the user may be zooming in and out to fix/clean various narrow wavelength range regions of the spectrum, we recommend that he/she first find a zoom range that nicely shows the entire spectrum and hit 'a' for **A**bsolute zoom level. Whenever the user needs to return to the entire spectrum, type 'w' for **W**hole spectrum.
5. The user can now clean and/or smooth the spectrum. Although the spectrum can be cleaned as many times as possible, the spectrum can only be smoothed once. That is, the user can continue to clean the spectrum after he/she has smoothed it, but not vice versa.

8.3 Cleaning a Spectrum

6. The user has two options to clean a spectrum:

- **Fixing the spectrum:** To **Fix** a region of the spectra, type 'f' and then press and release the left-most mouse button on the left and right side of the bad region. The pixels in the user selected wavelength are replaced using the edge pixels to define a line. Type 's' to **Save** the edit or 'u' to **Undo** the edit. Once an edit has been saved, it cannot be undone.
- **Removing the spectrum:** To **Remove** a region of the spectrum and replace the pixel values with NaN, type 'r' and then press and release the left-most mouse button on the left and right side of the bad region. The pixels in the user selected wavelength range will be set to NaN. 's' to **Save** the edit or 'u' to **Undo** the edit. Once an edit has been saved, it cannot be undone.

8.4 Smoothing a Spectrum

7. The user has two options to smooth a spectrum.

- Savitzky-Golay (SG) smoothing, which is described in detail in Numerical Recipes, will smooth the spectrum while preserving the average resolving power. Xcleanspec will automatically provide an estimate of the best SG window in units of pixels (in Box 3) based on the slit width. The best window size is typically 1 to 2 times the slit width, although we have found that for the 0.3 arcsecond slit, 1.5 times the slit width does nothing. The degree of the smoothing function can also be chosen (in Box 3), but must always be less than the window size.

***Note:** Please check the final spectrum to make sure you are happy with the results.*

- Gaussian smoothing will smooth the spectrum with a Gaussian kernel with the requested FWHM (in Box 3). Note since the resolving power changes as a function of wavelength, only the average resolving power will be modified. The default FWHM is the slit width given in pixels.

8.5 Write the File to Disk

8. When the user is done editing and/or smoothing the spectrum, give the root of the output file name in the **File Name** field (the .fits suffix will be automatically appended to the output name) and click on the **Write File** button in Box 4. If the user wishes to append a string to the input file name, s/he can click on the **Copy Input Name** button in Box 4 and the original filename will be copied in the **File Name** field. The spectrum will be displayed in

the `xvspec` GUI. Please see §10.6 for an example of the FITS header keywords added by Spextool if the spectrum has been smoothed in any way.

9 FAQ

1. *Are the wavelengths returned by Spextool in vacuo or air?*

All wavelengths generated by Spextool in are in vacuo.

2. *My calibration files do not have the prefixes “flat” and “arc” or my data are so old that I cannot use the Cal Panel.*

3. *How do I convert the Spextool FITS files to something useful like ASCII?*

See §2.10

4. *Spextool crashes when it attempts to locate the orders.*

Sometimes the order location routine will fail and the polynomial fits (green lines) will not follow the edges of an order(s). The most common reason (although not the only one) for this is that the ‘guess positions’ (red stars that are plotted in `ximgtool` during the order location process) are not sufficiently close to the center of the orders (probably because the grating was not set at the nominal position assumed by the software). Since the grating positions for the XD modes have changed slightly during the lifetime of SpeX, it is not possible to have a single set of guess positions that covers all grating positions. Therefore it may be necessary for the user to adjust these guess positions. The text files with the guess positions are located in `DIR/Spextool/instrument/SpeX/data/` where `DIR` is the directory where Spextool was installed. Each mode (ShortXD, LongXD, LowRes15) has a corresponding text file called `mode.dat` (e.g. `ShortXD.dat`). For example, at the bottom of the `ShortXD.dat` file you will find,

```
GUESSPOS_01= 454.0 170.0
GUESSPOS_02= 507.0 331.0
GUESSPOS_03= 551.0 457.0
GUESSPOS_04= 560.0 597.0
GUESSPOS_05= 627.0 741.0
GUESSPOS_06= 801.0 890.0
```

These are the (x,y) guess positions for the 6 orders, starting from the bottom of the array and moving upwards, as seen in `ximgtool`. The (0,0) point is located at the lower left of the image. If the guess position for an order needs to be edited because the order location routine is failing, the user should first load a raw flat into `ximgtool`. The user will have to rotate the raw flat image (all modes) by selecting `Zoom->Flip Y (7)` in pull down menu. The rotated image should appear like the images loaded by the main Spextool GUI. Using the cursor, determine a new (x,y) guess position for the offending order keeping in mind the new guess position should be located near the center of the order and away from the cracks and bad pixels. The (x,y) position should then be entered into the appropriate ‘mode’.dat file after the equal sign for the `GUESSPOS_0x` keywords.

5. *Spextool crashes when it attempts to create the wavelength calibration or it gives some message about not having enough lines.*

10 FITS Headers

10.1 Spextool

10.1.1 Flat Field Header

```
EDGEDEG =                      4 / Degree of the polynomial fit to order edges
NORDERS =                      7 / Number of orders identified
ORDERS = '3,4,5,6,7,8,9'      / Orders identified
PLTSCALE=          0.100000 / Plate scale (arcseconds per pixel)
SLTH_PIX=          150 / Slit height in pixels
SLTH_ARC=          15.0000 / Slit height in arcseconds
SLTW_PIX=          3.00000 / Slit width in pixels
SLTW_ARC=          0.300000 / Slit width in arcseconds
RP      =          2000 / Resolving power
ROTATION=          0 / IDL ROTATE value
VERSION = '4.0' / Spextool version
DARK    = 'None' / Dark frame
ODR03RMS=          0.0328439 / RMS deviation of the surface fit to order 03
ODR04RMS=          0.0358233 / RMS deviation of the surface fit to order 04
ODR05RMS=          0.0406168 / RMS deviation of the surface fit to order 05
ODR06RMS=          0.0335372 / RMS deviation of the surface fit to order 06
ODR07RMS=          0.0289770 / RMS deviation of the surface fit to order 07
ODR08RMS=          0.0300723 / RMS deviation of the surface fit to order 08
ODR09RMS=          0.0340442 / RMS deviation of the surface fit to order 09
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy COMMENT
and Astrophysics', volume 376, page 359; bibcode 2001A&A...376..359H
COMMENT = 'Flat'
ODR03.XR= '4,2043' / Extraction range for order 03
ODR04.XR= '4,2043' / Extraction range for order 04
ODR05.XR= '4,2043' / Extraction range for order 05
ODR06.XR= '4,2043' / Extraction range for order 06
ODR07.XR= '4,2043' / Extraction range for order 07
ODR08.XR= '200,2043' / Extraction range for order 08
ODR09.XR= '660,2043' / Extraction range for order 09
ODR03.B1=          352.003416417 / a0 edge coefficient for bottom of order 03
ODR03.B2=          -0.227866947257 / a1 edge coefficient for bottom of order 03
ODR03.B3=          4.68464870313E-05 / a2 edge coefficient for bottom of order 03
ODR03.B4=          -4.19718263570E-09 / a3 edge coefficient for bottom of order 03
ODR03.B5=          3.48388013381E-13 / a4 edge coefficient for bottom of order 03
ODR03.T1=          495.646591938 / a0 edge coefficient for top of order 03
ODR03.T2=          -0.229211077820 / a1 edge coefficient for top of order 03
ODR03.T3=          4.69173873272E-05 / a2 edge coefficient for top of order 03
ODR03.T4=          -4.36691606470E-09 / a3 edge coefficient for top of order 03
ODR03.T5=          3.58270647837E-13 / a4 edge coefficient for top of order 03
ODR04.B1=          598.962923739 / a0 edge coefficient for bottom of order 04
ODR04.B2=          -0.250797271707 / a1 edge coefficient for bottom of order 04
ODR04.B3=          7.17724648335E-05 / a2 edge coefficient for bottom of order 04
ODR04.B4=          -9.22474764275E-09 / a3 edge coefficient for bottom of order 04
```

ODR04.B5= 1.06379701194E-12 / a4 edge coefficient for bottom of order 04
 ODR04.T1= 745.758454012 / a0 edge coefficient for top of order 04
 ODR04.T2= -0.252955430139 / a1 edge coefficient for top of order 04
 ODR04.T3= 7.32562150296E-05 / a2 edge coefficient for top of order 04
 ODR04.T4= -1.03009488865E-08 / a3 edge coefficient for top of order 04
 ODR04.T5= 1.28191135922E-12 / a4 edge coefficient for top of order 04
 ODR05.B1= 844.756003190 / a0 edge coefficient for bottom of order 05
 ODR05.B2= -0.321844987981 / a1 edge coefficient for bottom of order 05
 ODR05.B3= 0.000104275268721 / a2 edge coefficient for bottom of order 05
 ODR05.B4= -1.75104209123E-08 / a3 edge coefficient for bottom of order 05
 ODR05.B5= 2.23526204197E-12 / a4 edge coefficient for bottom of order 05
 ODR05.T1= 994.481185193 / a0 edge coefficient for top of order 05
 ODR05.T2= -0.324481592875 / a1 edge coefficient for top of order 05
 ODR05.T3= 0.000104849548992 / a2 edge coefficient for top of order 05
 ODR05.T4= -1.74806023712E-08 / a3 edge coefficient for top of order 05
 ODR05.T5= 2.16430173598E-12 / a4 edge coefficient for top of order 05
 ODR06.B1= 1130.42148296 / a0 edge coefficient for bottom of order 06
 ODR06.B2= -0.434910447854 / a1 edge coefficient for bottom of order 06
 ODR06.B3= 0.000149657344313 / a2 edge coefficient for bottom of order 06
 ODR06.B4= -2.95561940809E-08 / a3 edge coefficient for bottom of order 06
 ODR06.B5= 3.85811111285E-12 / a4 edge coefficient for bottom of order 06
 ODR06.T1= 1283.54269029 / a0 edge coefficient for top of order 06
 ODR06.T2= -0.439059502296 / a1 edge coefficient for top of order 06
 ODR06.T3= 0.000151016446113 / a2 edge coefficient for top of order 06
 ODR06.T4= -2.98026050053E-08 / a3 edge coefficient for top of order 06
 ODR06.T5= 3.84264442404E-12 / a4 edge coefficient for top of order 06
 ODR07.B1= 1479.42208267 / a0 edge coefficient for bottom of order 07
 ODR07.B2= -0.597299186236 / a1 edge coefficient for bottom of order 07
 ODR07.B3= 0.000213134949078 / a2 edge coefficient for bottom of order 07
 ODR07.B4= -4.55713299917E-08 / a3 edge coefficient for bottom of order 07
 ODR07.B5= 5.72981307681E-12 / a4 edge coefficient for bottom of order 07
 ODR07.T1= 1636.64951570 / a0 edge coefficient for top of order 07
 ODR07.T2= -0.603632610257 / a1 edge coefficient for top of order 07
 ODR07.T3= 0.000215608318519 / a2 edge coefficient for top of order 07
 ODR07.T4= -4.63052650510E-08 / a3 edge coefficient for top of order 07
 ODR07.T5= 5.83057185136E-12 / a4 edge coefficient for top of order 07
 ODR08.B1= 1914.53170675 / a0 edge coefficient for bottom of order 08
 ODR08.B2= -0.823739988379 / a1 edge coefficient for bottom of order 08
 ODR08.B3= 0.000301533850182 / a2 edge coefficient for bottom of order 08
 ODR08.B4= -6.69913639396E-08 / a3 edge coefficient for bottom of order 08
 ODR08.B5= 8.02696255779E-12 / a4 edge coefficient for bottom of order 08
 ODR08.T1= 2076.68795462 / a0 edge coefficient for top of order 08
 ODR08.T2= -0.832388360367 / a1 edge coefficient for top of order 08
 ODR08.T3= 0.000304147220698 / a2 edge coefficient for top of order 08
 ODR08.T4= -6.73195243463E-08 / a3 edge coefficient for top of order 08
 ODR08.T5= 8.01440328332E-12 / a4 edge coefficient for top of order 08
 ODR09.B1= 2463.10256764 / a0 edge coefficient for bottom of order 09
 ODR09.B2= -1.13290064686 / a1 edge coefficient for bottom of order 09
 ODR09.B3= 0.000419115619819 / a2 edge coefficient for bottom of order 09
 ODR09.B4= -9.29869838241E-08 / a3 edge coefficient for bottom of order 09
 ODR09.B5= 1.04222432357E-11 / a4 edge coefficient for bottom of order 09

```

ODR09.T1=          2635.01085142 / a0 edge coefficient for top of order 09
ODR09.T2=          -1.15643436838 / a1 edge coefficient for top of order 09
ODR09.T3=          0.000435601533884 / a2 edge coefficient for top of order 09
ODR09.T4=          -9.95786958782E-08 / a3 edge coefficient for top of order 09
ODR09.T5=          1.14980117722E-11 / a4 edge coefficient for top of order 09

```

```

##### Xspextool History #####

```

```

HISTORY This flat was created by scaling the files flat-00001.a.fits,
HISTORY flat-00002.a.fits, flat-00003.a.fits, flat-00004.a.fits,
HISTORY flat-00005.a.fits to a common median flux value and then median
HISTORY combining the scaled images. The variance is given by
HISTORY (MAD2/nimages) where MAD is the median absolute deviation and
HISTORY nimages is the number of input images.
END

```

10.1.2 Combined Images Header

```

NIMGS      =          5 / Number of images combined.
PAIRSUB    =          0 / Pair subtraction?: 1=yes, 0=no.
ITOT       =          23.1670 / Total integration time PER BEAM
COMMENT    = 'Flat'

```

```

##### Xspextool History #####

```

```

HISTORY This image was created by Mean (Mean Error) combining the images
HISTORY flat-00001.a.fits, flat-00002.a.fits, flat-00003.a.fits,
HISTORY flat-00004.a.fits, flat-00005.a.fits. Each order within an image was
HISTORY first scaled to the median flux value of all of the pixels in that
HISTORY order in all of the images. This median flux level was subtracted
HISTORY off on a column by column basis within each order.
END

```

10.2 Xcombspec

```

ITOT      =          150.000 / Total integration time (sec)

```

```

##### Xcombspec History #####

```

```

HISTORY The files spectra0080.fits, spectra0081.fits, spectra0082.fits,
HISTORY spectra0083.fits, spectra0084.fits, spectra0085.fits,
HISTORY spectra0086.fits, spectra0087.fits, spectra0088.fits,
HISTORY spectra0089.fits were combined. Aperture 01 Info: The scale
HISTORY factors were determined using order 05. The scale factors are
HISTORY 1.14589, 0.992213, 0.883621, 0.956446, 0.964207, 1.01370, 0.867263,
HISTORY 1.00853, 1.14901, 1.64877. The median RMS deviation in each order is

```

HISTORY 3.92413, 3.41298, 2.01570, 2.64838. The spectra were combined using
HISTORY a Robust Weighted Mean. The robust threshold was 8.00000.
END

10.3 Xtellcor

10.4 Xmergeorders

Xmergeorders History

HISTORY This merged spectrum was derived from aperture 01 of file
HISTORY WISE1741-4642.fits. The scaled factors for orders 3, 4, 5, 6 are
HISTORY 1.00000, 1.00000, 1.00000, 1.00000 respectively.

10.5 Xmergexd

10.6 Xcleanspec

Xcleanspec History

HISTORY This spectrum has been convolved with a Gaussian of FWHM=5.33330 pixels.

11 Miscellaneous Notes

11.1 Spextool: Calibration Frames with Non-standard Prefixes

Continue with the extraction process in §3.3.2.

11.2 Spextool: Wavelength Calibration

It is possible - although usually not necessary - to examine the result of the cross-correlation by turning on the Plot X-Correlate button in the Wave Cal Parameters panel in the Other Base before the extraction is performed. If this button is turned on, Spextool will display the result of the cross-correlation, and a Gaussian fit (in red) to the largest peak in the cross-correlation spectrum, from which it will determine the pixel shift. It will then ask the user if the solution is acceptable. If it is not an acceptable fit, or if the Auto X-Correlate button is turned off in the Other Base, the xgetoffset widget will appear and will display the stored arc spectrum and the observed/extracted arc spectrum. The user must then identify the same line in each spectrum by clicking on the lines with the left-most mouse button. The region around the selected line in both arc spectra, and a Gaussian fit to the two lines, will be displayed in the window next to each spectrum. Spextool will determine the pixel shift between the two spectra based on the center position of the two Gaussian fits. When the user is satisfied, s/he clicks the Accept button and Spextool will then determine the wavelength calibration solution, which will be applied later to the extracted object spectra.

The wavelength solution determined by Spextool can also be examined by selecting the Plot Residuals button in the Wave Cal Parameters panel on the far right hand side of the Other Base. When this button is selected, Spextool will display a plot of the residuals (in Angstroms) of the fit to the wavelength solution as a function of SpeX order (at the top) and as a function of column across the array (at the bottom). Click on the "Continue" button and Spextool will proceed with the remaining steps in the extraction process.

The user can also decide to simply accept a "Stored" wavelength solution, that has been previously determined and stored on disk, rather than have Spextool attempt to determine the wavelength solution from the observed arc frames. When using wide slits (1.6 and 3.0 arcseconds), this is the required method of carrying out wavelength calibration. In these cases the user should select the Use Disk Solution button at the bottom of the Wave Cal Parameters panel (far right hand side) in the Other Base. Spextool will automatically determine the offset between stored arc and the extracted one. This offset is then applied to the pre-determined wavelength solution stored on disk. Again, if the Auto X-Correlate button is turned off in the Other Base, the xgetoffset widget will appear and the user will be required to identify the same line in both the observed and the stored arc spectra, as described above. Spextool will use the shift determined from the identified lines as an offset which will be applied to the pre-determined wavelength solution stored on disk.

(Alternatively, if the observer is using wide slits for her/his objects, s/he could choose to adopt

the wavelength calibration derived from arc spectra obtained with the 0".3 slit. This would require that the observer switch to the narrow slit for the arc frames obtained along with the wide slit object frames. A separate cal macro would be needed for this procedure.)

Xcombspec

As of v3.3, xcombspec applies a single scale factor, determined from the user-selected order, to all the orders. Older versions determined separate scale factors for each order. The switch to a single scale factor per spectrum was made because (1) we found that the use of separate scale factors for each order resulted in mismatches in the flux levels in the order overlap regions in the final combined spectrum; and (2) scale factors could not be determined reliably in those orders with low S/N. The use of a single scale factor determined from a high S/N order obviates problem (2) while simultaneously yielding excellent flux level agreement in the order overlap regions of the combined spectrum.

Nevertheless, the adoption of a single scale factor has revealed another challenge for the combining procedure and software. If there were no systematic/instrumental effects, the use of a single scale factor for a given spectrum across all orders should give the same result as applying separate scale factors for each order. However, as explained above, we have found that, after adopting a single scale factor for each spectrum across all orders, the slopes of spectra recorded by SpeX for a single object within a block of 5 A-B pairs taken one after another can vary by a few percent.

Although it is not yet clear exactly what causes this variation, we believe it results from a combination of physical effects (flexure, guiding errors, atmospheric dispersion, variable transmission, etc.) and it does not appear to be due to any procedures involved in the data reduction. We believe that xcombspec incorporates the appropriate procedure for combining these spectra (yielding the median spectrum with the correct slope). Nevertheless, **we urge users to perform the same steps and use the same statistics for their standard stars as for their objects.**

12 Version History

The most recent version of Spextool is v4.1.

v4.1: 2015-01-XX

- General bug fixes.
- Added a new flag that identifies pixels that cannot be optimally extracted.
- `xvspec` can now write Spextool FITS files and ASCII files to disk.
- `xvspec` can now display both the A and B extractions. The user can switch between buffers by typing 'a' or 'b' or using the pulldown menus.
- `xvspec` can now plot multi-order extractions in a single plot window. This method is now known as “Continuous” display while the older method is known as “Ladder” display.
- `xvspec` can now plot the atmospheric transmission on the spectra (use Plot pulldown menu).

v4.0: 2015-01-XX

- A full pdf manual supercedes the ASCII help files.
- Spextool now lets the user choose the file prefix in the read mode panel by a pulldown menu instead of having to type them in.
- A median spatial profile can be used for optimal extraction instead of a wavelength dependent one (useful in low S/N cases).
- The cal panel now has a prefix column to allow for different sky frames with different file prefixes.
- Added an ITOT keyword to the output FITS files.
- The default plot ranges are now derived intelligently to avoid bad pixels.
- Major internal re-write to allow incorporating new instruments easier.
- Ximgtool has been completely re-written and boasts more capabilities.
- The appearance of the ximgtool and xvspec widgets are improved.
- Lines and symbols plotted on ximgtool are now permanent when the user zooms or pans around the image.

- More FITS headers keywords have been added to the output files and the histories are now labelled and self-consistent.
- Spextool will now check to make sure that there are not multiple file names with the same index number but a different prefix (e.g. spc0001.a.fits and arc0001.a.fits).
- Atmospheric transmission curves at the correct resolving power are now displayed in xcleanspec and xtellcor.
- Output images are now stored as multi-extension FITS files.
- Wavecal files are now full array images that include the wavelength solution and the spatial solution.
- Almost all routines have the prefix 'mc_' in order to avoid conflicts with other libraries.
- Spextool now includes a flag array on its output that allow the user to identify flux density values that have been affected by bad pixels or saturated pixels.
- Quality assurance plots are generated for all wavelength solutions except the prism mode.

v3.4: 2005-11-08

- Fixed image math base in ximgtool
- Fixed an xmergexd error and added both the SXD and LXD HISTORY fields to the final FITS file
- Fixed bug when concatenating headers that do not have the same sized HISTORY fields
- Renamed xfit2text to xspex2text and fits2text to spex2text
- Updated plotting character sizes to scale with the plot window sizes
- Added a routine to test the seeing for optimal extraction (See step 16).
- Added an IDLWAVE catalog file
- Added ability to specify aperture positions independently in each order
- Postscript plots (ShortXD.IDs.ps, LongXD.IDs.ps) showing the identification of the lines used for wavelength calibration are included in Spextool/data
- Fixed bug in xtellcor_finish regarding the YUNITS FITS keyword.
- Spextool is now Windows compatible (thanks to Dan Clemens, BU and Joshua Kim, UA)

v2.1: 2001-Oct-09

- Fixed bugs in xcombspec
- Added xsmoothspec widget to smooth spectra by a Gaussian with FWHM equal to the slit width in pixels
- Added a fits2text program to convert a SpeX FITS file to a text file
- Improved bad pixel replacement
- Added a data set to allow the user to practice using Spextool

v2.0: 2001-Aug-17, Major revisions

- Errors are now propagated through the extraction process. An error vector is now produced and appears as a third dimension in the FITS array or another column in the text array.
- All output names (i.e. arcs, flats, etc) should NOT have the suffix .fits added now. Spextool will add it automatically. When loading images in using full names, the entire name, including the .fits, should be entered.
- Xplotprofiles now shows the raw data and has cursor tracking.
- Xvspec can show the error spectra and compute the signal-to-noise in each spectrum.
- Xvspec can now smooth the spectra (convolve with a Gaussian of $\text{FWHM} = \text{npixels}$) and propagate the error.
- To launch a zoom window (xzspec) in xvspec, click on the order you want to examine. Xzspec is fully resizable. To learn the cursor commands, type 'h' in the plot window.
- A new widget called xmkcals allows the user to construct the flats and arcs for the entire night.
- The xcombspec widget has been completely redesigned to allow more user input.

v1.5: 2001-Mar-09

- Improved wavelength calibration for the LXD1.9 and LXD2.3. See step 8.
- Improved flat fielding (To be described later).
- Prism mode can now be fully reduced.
- Modified Path input.
- XQTV can now perform image arithmetic (under file menu button).

- xcombspec has been modified to combine apertures if requested. This is useful when point source data is combined before being extracted. In this case, Spextool writes both apertures to the same file.
- Wavelength calibration now requires a user input which gives the pixel offset of an arc spectrum relative to a standard arc spectrum.

v1.4: 2000-Dec-18

- Fixed bug where the spectra returned using the extended source extraction base WERE NOT in DN/s. The values are now returned as DN/s.
- Added Combine base (see below).
- Fixed a bug which made the spectra appear to have some sort of fringing when small apertures, < 1 arcsecond, were used.
- Modified the way the arcs, flats and skys are stored. As a result, arcs, flats and skys made using earlier versions of Spextool have to be modified as follows: At an IDL prompt:

```
IDL> i = readfits('filename',hdr)
IDL> writefits, 'filename',rotate(i,7),hdr
```

The flats, arcs, and skys can now be used with version 1.4.

v1.3: 2000-Oct-24

- bug fixes in xcombspec

v1.2: 2000-Oct-20

- added xcombspec
- modified PS extraction
- added description of xvspec

v1.1: 2000-Oct-18

- Bug fixes and added a sky base

v1.0: 2000-Oct-13

- Original release

A Pre-Upgrade SpeX

Detectors, Array Controllers

SpeX was commissioned on the IRTF in May of 2000. The spectrograph camera was equipped with a 1024×1024 InSb array and the guide camera was equipped with a 512×512 InSb array. SpeX used an in-house array controller to operate the two arrays. The spectrograph controller is known as ‘Bigdog’ and the guider as ‘Guidedog’. Bigdog and Guidedog are housed in a VME64 rack mount with independent VME64 backplanes in the telescope control room. Each controller houses a Sparc engine running Unix, a DSP-based single board computer, a fiber-optic link to the cryostat-mounted electronics, and a board for time-stamping data. The DSPs perform the time-critical tasks of pixel clocking, pixel data acquisition, and low-level pixel processing. The Unix computer performs upper level control functions, including loading code into the DSPs and commanding them, controlling the instrument via the GUI, and higher-level data processing and display.

The cryostat-mounted electronics provides for the complete control of array readout and digital conversion of pixel analog signal values. The spectrograph and guider electronics are housed in a single rack mount chassis that is mounted to the side of the cryostat to keep the high-frequency analog lines to the arrays as short as possible. Array clocking patterns and programmable biases (most of the biases are hardwired) are transmitted over the fiber-optic link from the clocking DSPs, and into 12-bit digital-to-analog voltages to drive the arrays. Each of the 32 spectrograph array outputs and each of the 8 guider array outputs are conditioned by a preamplifier circuit and output to its own 2 MHz, 16-bit A/D converter. The converted digital values are then transmitted over the optical fibers to the pixel buffering DSPs in the computer. transferred onto a fiber-optic interface board for transmission to the pixel buffering DSPs in the computer.

All 32 channels of the 1024×1024 Aladdin InSb spectrograph array are read out simultaneously. There are eight channels per array quadrant (i.e. 512×512 sub-arrays). Channel one reads out column one, channel two reads out column two etc. repeating every eight columns across the array quadrant. Given slight variations in channel gain and ‘burst’ noise on read out this results in a distinctive array read out pattern at very low signal levels: slight offsets between the four quadrants and ‘sawtooth’ column to column signal variations. The one quadrant 512×512 Aladdin InSb guider array just shows the eight column structure.

The Aladdin spectrograph array has a gain of 11.5 electrons per data number ($e^- \text{ DN}^{-1}$) and a $15 \mu\text{sec pixel}^{-1}$ read noise of about $40 e^- \text{ RMS}$ per correlated double sample (CDS) and about $15 e^- \text{ RMS}$ for 32 non-destructive reads (NDRs). The blanked off dark current is about $0.2 e^- \text{ sec}^{-1}$ but the effective dark current is more like $1 e^- \text{ sec}^{-1}$ due to image persistence. The engineering quality Aladdin guider array has a gain of $14 e^- \text{ DN}^{-1}$ and a $10 \mu\text{sec pixel}^{-1}$ read noise of about $60 e^- \text{ RMS}$ per CDS and an effective dark current of $10 e^- \text{ sec}^{-1}$.

Spextool and Instrument Modes

Spextool can reduce SpeX data obtained with the ShortXD, LongXD1.9, LongXD2.1, LongXD2.3,

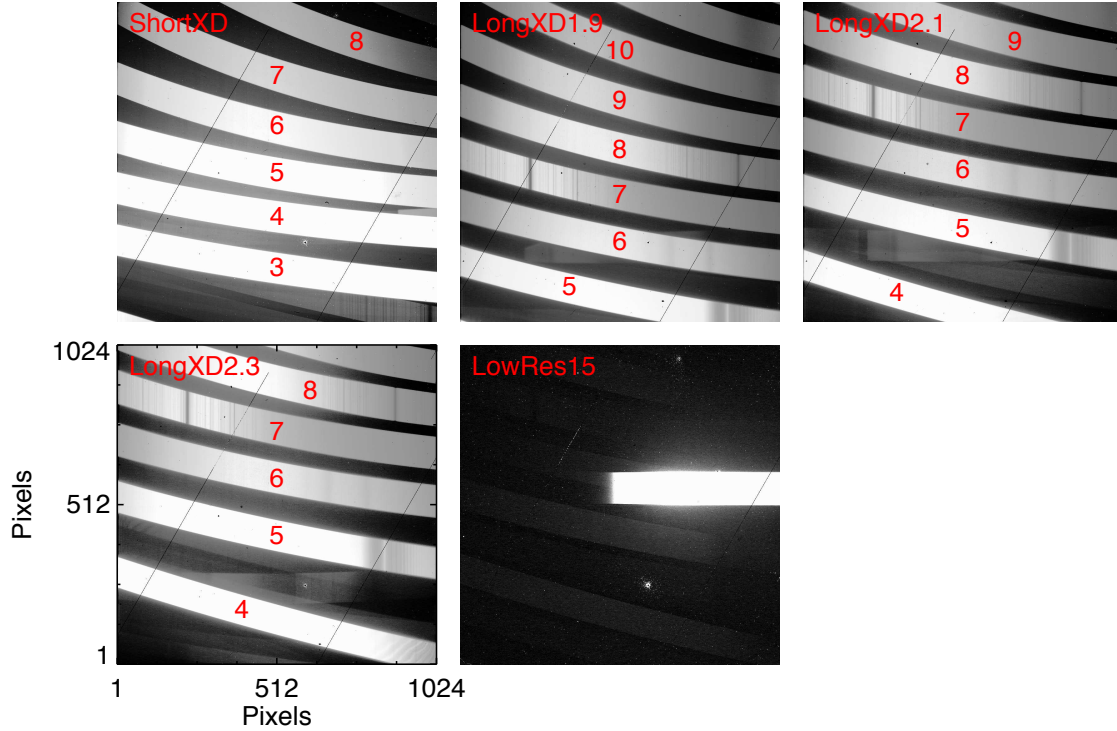


Figure 4: Flat-field exposures for the five SpeX modes that are compatible with Spextool.

and LowRes15 modes. Figure 4 show flat field exposures for each of these modes and Tables 5 give the wavelengths covered by each of the orders in the cross-dispersed modes. The LowRes15 mode consists of a single order dispersed with a double-pass prism and covers the wavelengths from 0.7 to 2.5 μm .

Table 5: XD Mode Wavelength Coverage for SpeX

Order	Wavelengths (μm)			
	ShortXD	LongXD1.9	LongXD2.1	LongXD2.3
10	...	1.92–2.18
9	...	1.98–2.42	2.23–2.42	...
8	0.81–0.90	2.23–2.73	2.24–2.73	2.40–2.73
7	0.81–1.03	2.55–3.12	2.55–3.12	2.55–3.12
6	0.94–1.20	2.97–3.64	2.97–3.64	2.97–3.64
5	1.13–1.45	3.56–4.19	3.56–4.19	3.56–4.19
4	1.41–1.81	...	4.45–5.04	4.45–5.44
3	1.88–2.42

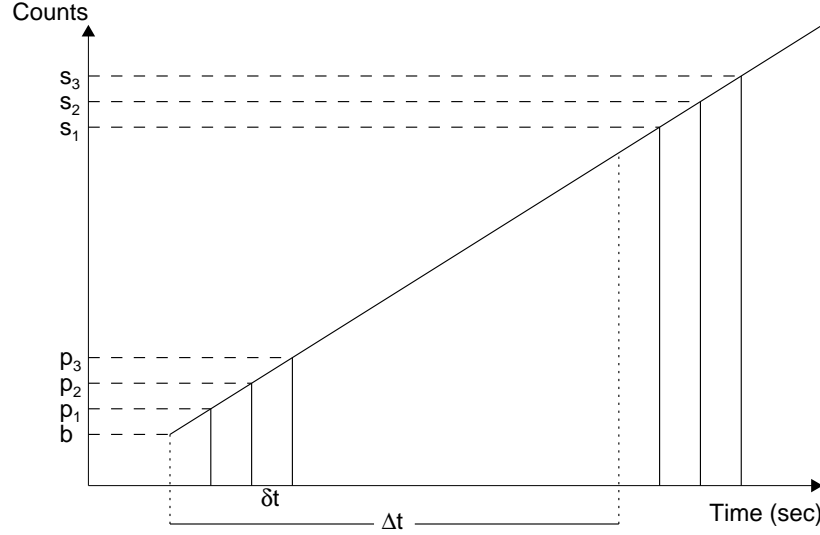


Figure 5: A schematic of the signal recorded by a given pixel as a function of time on a perfectly linear detection. The two dotted vertical lines represent the starting time of the first read of the pedestal and the start of the first read of the signal. Each read is assumed to last δt sec. Each solid vertical line represents the end of a read. The exposure time is Δt sec.

Data Format

The data are written to disk as FITS images. The value written to each pixel is computed as follows³. Consider Figure 5 which shows a schematic of the signal recorded by a given pixel as a function of time on a perfectly linear detection with the number of non-destructive reads (n_r) set to 3. After the array is reset to the bias level b , the array is immediately read out nondestructively n_r times (in this case $n_r=3$) which provides an estimate of the average *pedestal* level. After the exposure time Δt , the array is again read out nondestructively n_r times to provide an estimate of the average *signal* level. The value of each pixel in the FITS image is given by:

$$S = \sum_{i=1}^{n_r} s_i - \sum_{i=1}^{n_r} p_i \quad (6)$$

We note that in principle, each read must be corrected for nonlinearity since each read occurs at a different location on the linearity curve. However, since only the difference between the sum of the signal reads and the sum of the pedestal reads is stored to disk, we instead estimate the average signal and pedestal levels and correct each for nonlinearity following the technique described in Vacca, Cushing, & Rayner (2004, PASP, 116, 352).

³The following description closely follows that of Vacca, Cushing, & Rayner (2004, PASP, 116, 352).