APO TripleSpecTool User's Guide

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1 Introduction

APOTripleSpecTool is a widget-based IDL package modified from SpexTool, which was written by Mike Cushing and Bill Vacca for SpeX (http://irtfweb.ifa.hawaii.edu/~spex/) spectrograph data. This tool converts TripleSpec images to one-dimensional telluric-absorption-corrected absolute-calibrated spectra with flexibility for selecting spectral apertures for both point and extended sources.

2 Installation

If you have a previous version of Spextool, you must delete it since you will be required to download v3.5beta and many of the routines are similar. Cormasstool will also no longer work with this version of Spextool.

2.1 Computer Requirements

- APOTripleSpecTool & Spextool will **NOT** run under versions of IDL earlier than 5.6 and there are no plans to make it compatible with them.

- IDL Astronomy Users Library is necessary and can be downloaded from the following URL: http://idlastro.gsfc.nasa.gov/homepage.html

- This software currently works natively only under Unix, Linux or Mac operating systems. With quite a bit of setting up and effort, however, one can coax it into running under a Linux emulating environment for Windows, such as Cygwin.

- Spextool v3.5beta is necessary for APOTripleSpecTool.

2.2 Downloads

- SpexTool (36MB; last update: 7/16/2009): http://www.astro.virginia.edu/~mfs4n/tspec/user/tspectool/Spextool2_090716.tar.gz

- APOTripleSpecTool (156K; last update 7/16/2009): http://www.astro.virginia.edu/~mfs4n/tspec/user/tspectool/APOTriplespectool_090716.tar.gz

2.3 IDL Setup

Download the Spextool2 gzipped tar file, gunzip and unpack it by typing:

```
> tar zxvf Spextool2.tar.gz
```

This will create a directory called Spextool2, which is the package directory, and a number of sub-directories. Do the same for the APOTriplespectool tarfile.

For ease, you can unpack the tarfiles into a directory that is already part of your IDL path (e.g., `~/IDL_TOOL/`). In this way, it is not necessary to alter your shell such as .cshrc, .bash, or .idl.

However, if you need to unpack the tarfiles somewhere that is not already part in your IDL path, then you must modify your IDL path to include the Spextool2 and APOTriplespectool package directories. 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 machine, if the IDL path is defined in a .cshrc file, edit the .cshrc file to include the line `setenv IDL PATH +/packagedirectory:$IDL PATH` where `/packagedirectory` is the path to the package directory (e.g., `/home/user/idlpro/Spextool`). If there is no IDL PATH defined in the .cshrc file, then include the line `setenv IDL PATH +/packagedirectory`

3 Data Preparation

APOTripleSpecTool accepts the raw fits data files from TripleSpec on the Apache Point Observatory 3.5-meter telescope. No preparation or pre-processing should be necessary other than to make sure the files have a .fits extension. If you would like to view the raw images in IDL, you can do so using a SpexTool widget called ximgtool or open them with DS9 (http://hea-www.harvard.edu/RD/ds9/).

4 Quickstart Guide

The following is a brief summary of the order of the IDL GUI commands that you will need and what each will accomplish:

Xspextool – This program generates a flat field by using observations of Bright Quartz lamps and creates wavelength calibration files based off of the positions of airglow lines seen in on-source spectra. Once these calibrators have been generated, the target (point source or extended) is found and extracted.

Xcombspec – This routine inputs multiple extracted spectra generated from xspectool and combines them using one of numerous statistics.

Xtellcor, Xtellcor_basic, Xtellcor_finish – These routines allow a user to input their source of interest and an associated A0V standard star in order to remove telluric lines and flux-calibrate the science spectra. Xtellcor is used most often and provides the most customization. Whereas xtellcor uses a high-resolution model of Vega to remove intrinsic stellar features, Xtellcor_basic simply divides the object spectrum by the standard stars and multiplies the result by a blackbody. Xtellcor_finish takes a previously saved telluric correction function and applies it to a given spectrum.

Xmergeorders – The program merges the orders of telluric-corrected spectra.

5 Launching APOTripleSpecTool

- **Start IDL and bring up APOTripleSpecTool by typing `xspextool` in the IDL prompt.** This will launch the main window, called the Main Base. In general, a Base is a panel (or a set of panels) containing fields and buttons that the user fills-in/selects to control procedures carrying out the reduction.

- **Click on the Paths button in the middle of the Main Base.** This will bring up the Paths Panel. APOTripleSpecTool will automatically load the paths last entered by the user. APOTripleSpecTool assumes (but does not require) that the raw data, processed data needed for calibrations (e.g., flats and arcs), and completely reduced data will be kept in separate directories. While this need not be the case, it makes the reductions easier to keep track of (for humans). If you wish to adopt this structure, create 3 subdirectories and put all of your raw data in one of them. 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.** APOTripleSpecTool will remember these directories, so that next time you start it these fields will be loaded automatically. **Finally, click the Update Paths button to load the paths into memory.**

- **In the File Read panel above the Paths panel, make sure 'File Name' is selected** for the meantime, otherwise Spextool will search for files with a given prefix rather than the files you select.

- Click on the 'Other' section in the Main Base and **ensure that Error Propagation, Flat Fielding, and Fix Bad Pixels are enabled**. These setting are relatively self-explanatory. While not necessary, they will considerably improve the quality of your final spectra.

- While APOTripleSpecTool has a built-in routine for flagging and fixing bad pixels on-the-fly, you may construct your own bad pixel mask. Simply create a 2048x1024 FITS file populated with 0s and 1s, where '0' represents a bad pixel and '1' represents a pixel that varies in a predictable manner. The current bad pixel mask is located under the `APOTriplespectool/data/` directory and is named 'bmask.fits'. In order to use your custom mask, copy the file (with a different name) into that directory, then edit the 'BADPIXMASK' value in the 'APOTriplespec.dat' file.

6   Constructing Flat Fields

The first thing on the list involves constructing a flat field using Bright Quartz lamp frames taken during the night of the observing run. This lamp fills the slit and is continuous over the entire spectral region with no observable emission or absorption features, making it an ideal calibrator for removing artifacts due to variations in the pixel-to-pixel response. These observation must be done on the same night since miniscule changes in the position of the spectrum on the detector (caused by instrument flexor) can have adverse on your final product if not taken into consideration. For each slit that was used to observe your target, you should have corresponding Quartz lamps taken with the same slit.

- Click on 'Flat' in the Main Base (Figure figure1).

- Under 'Slit Width,' enter the size of the slit in both pixels and arcseconds, which will depend on what slit was used during the observation of interest:

  - 0.7 slit: 1.4/0.70
  - 1.1 slit: 2.2/1.08
  - 1.5 slit: 3.0/1.52
  - 1.7 slit: 3.4/1.69

  The size of each slit in arcseconds is well-known; and, theoretically, TripleSpec's samples at approximately 2 pixels per arcsec. We are currently exploring the observational values for the first parameter (Slit Width in Pixels). Thus far, we have determined that varying this parameter by ±0.2 from the values suggested above has no discernable difference. You are welcome to experiment with this value. **Note: If you have observations using the 0.7 slit, make sure you have downloaded the latest version of Spextool, which contains the atran5000.fits and atran6000.fits files in the data directory.**

- Click the 'Raw Flat Images' button and select the Bright Quartz lamp frames that were taken during the night of the observing run for the appropriate slit. You can select multiple files simultaneously by either clicking and dragging, clicking while the Shift button on the keyboard is depressed, or clicking while holding down the Control button on the keyboard.

- For now, leave the 'Full Dark Name' blank. Normally this option would remove a dark frame containing simply the noise generated by the detector, however, it currently appears to interfere with the order-finding routine.

- Choose a statistic for combining the individual flats (a typical choice is Median).

- Make sure 'Yes' is selected next to 'Normalize Flat.'

- Type in a desired output flat name (e.g. flat11-2008-05-09 where '11' refers to the 1.1 slit) and click 'Construct Flat.' The final, constructed flat is written to your cal directory (Figure figure2).

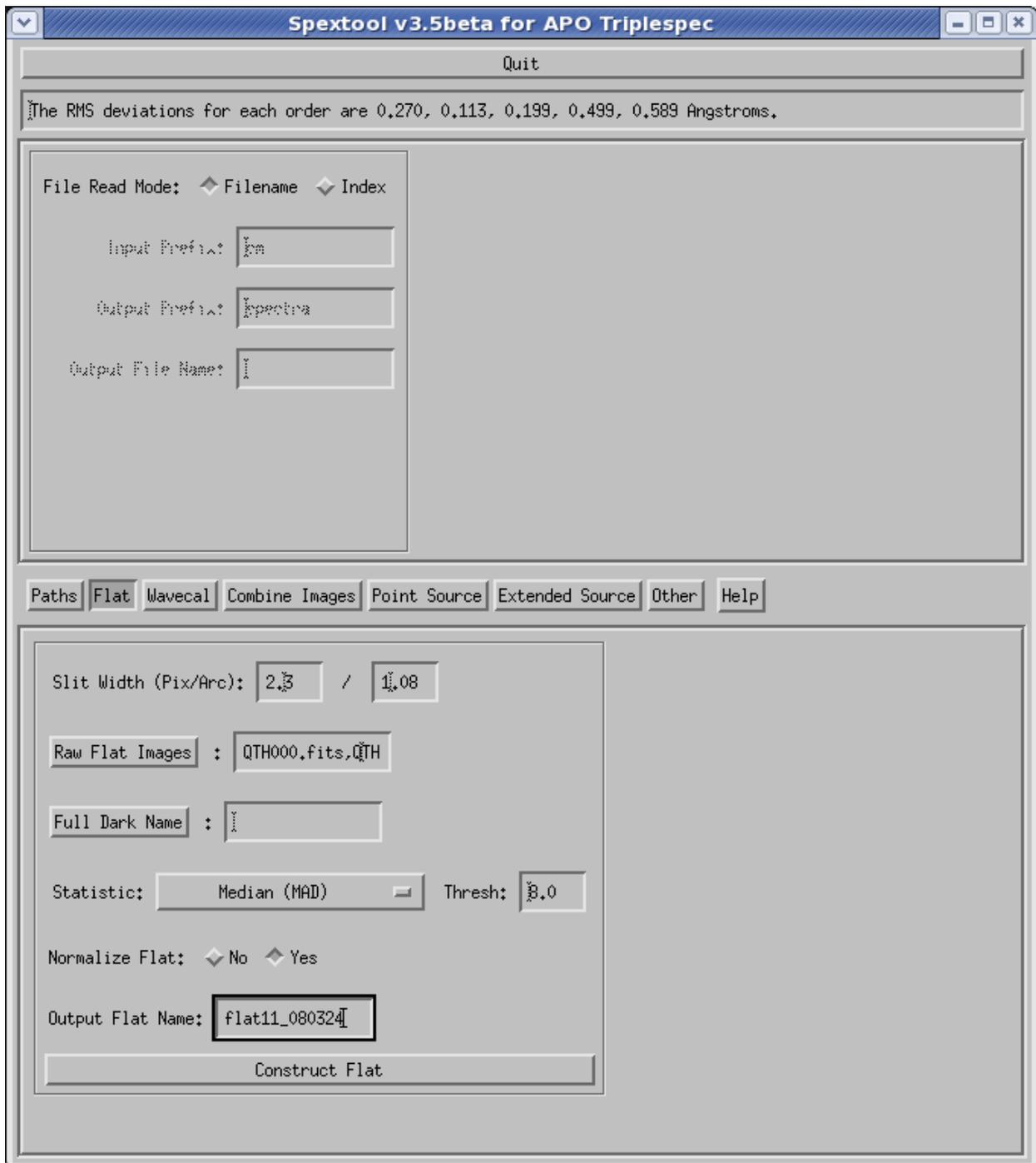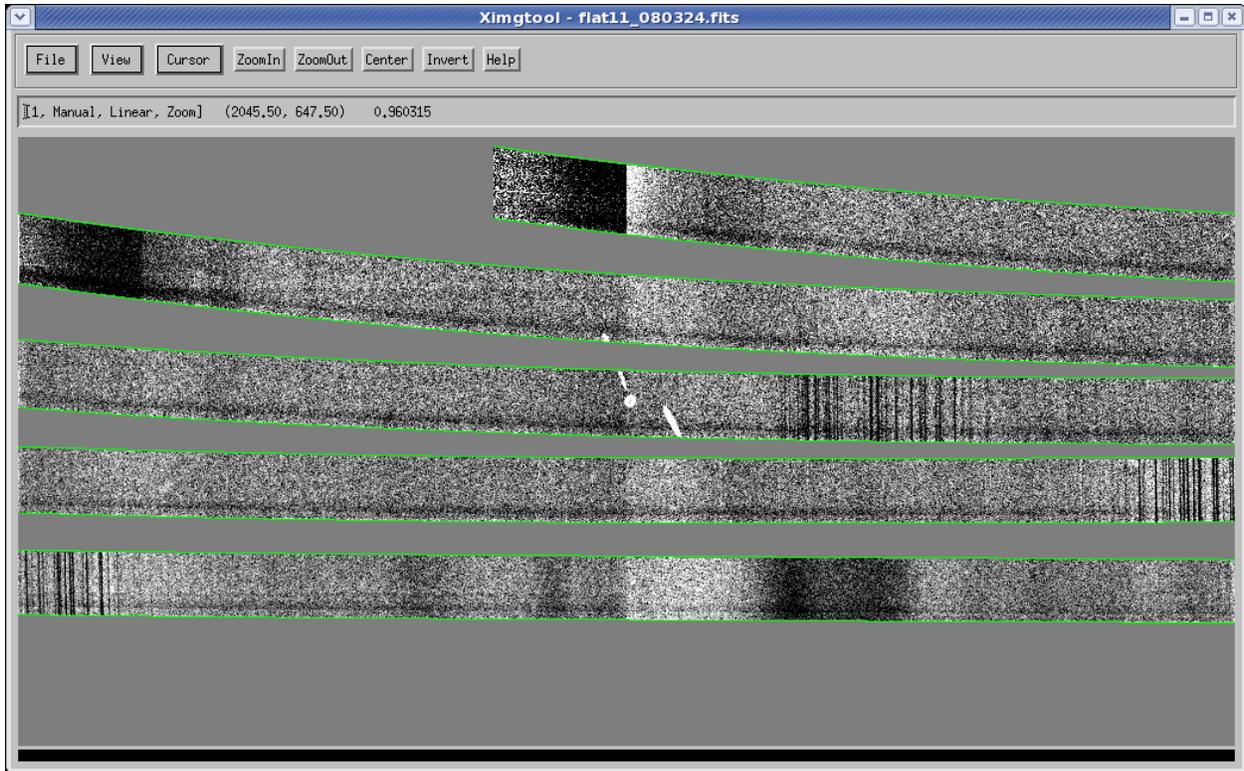Figure 1: *Panel for creating flat fields.*

Figure 2: *Typical output after constructing a flat field.*

7 Wavelength Calibration

Telluric airglow lines originating mainly from OH in the atmosphere are used to determine wavelength as a function of position for a given set of observations. As mentioned in the above section, these should be generated on at least a night-to-night basis. Since this method uses lines in the very spectra we intend to reduce, we are only limited by the number of observations with sky background in the center of the slit. Thus, you may find it useful to produce not just one wavelength calibration per night, but instead a wavecal file for each set of objects observed (i.e., each science target and each standard star).

Due to the curved nature of some of the orders on the detector, each pixel along a column (for any given order) is actually associated with a slightly different wavelength. This is particularly apparent with orders 6 and 7. However, APOTripleSpecTool currently utilizes a 1-dimensional wavelength calibration that simply associates each column with a particular wavelength; which, combined with the order curvature, produces an increasingly pronounced wavelength mismatch as you move further from the center of the slit. This mismatch becomes particularly noticeable when removing local sky background, but can be mitigated by choosing background close to the source (see Section subsubsection8.1.4 for more details). We are currently in the process of updating the software to take into account the order curvature.

- Click on the 'Wavecal' button to bring up the wavelength calibration base (Figure figure3).

- In order to construct the wavelength calibration file, APOTripleSpecTool requires an image file where the center of the spectral orders are empty of everything except for bright airglow (OH) lines.

- Click the 'Sky Images' button and choose multiple bright point source images (usually your science target or standard star works fine) with a relatively long integration time that have the point source far away from the center of the slit.

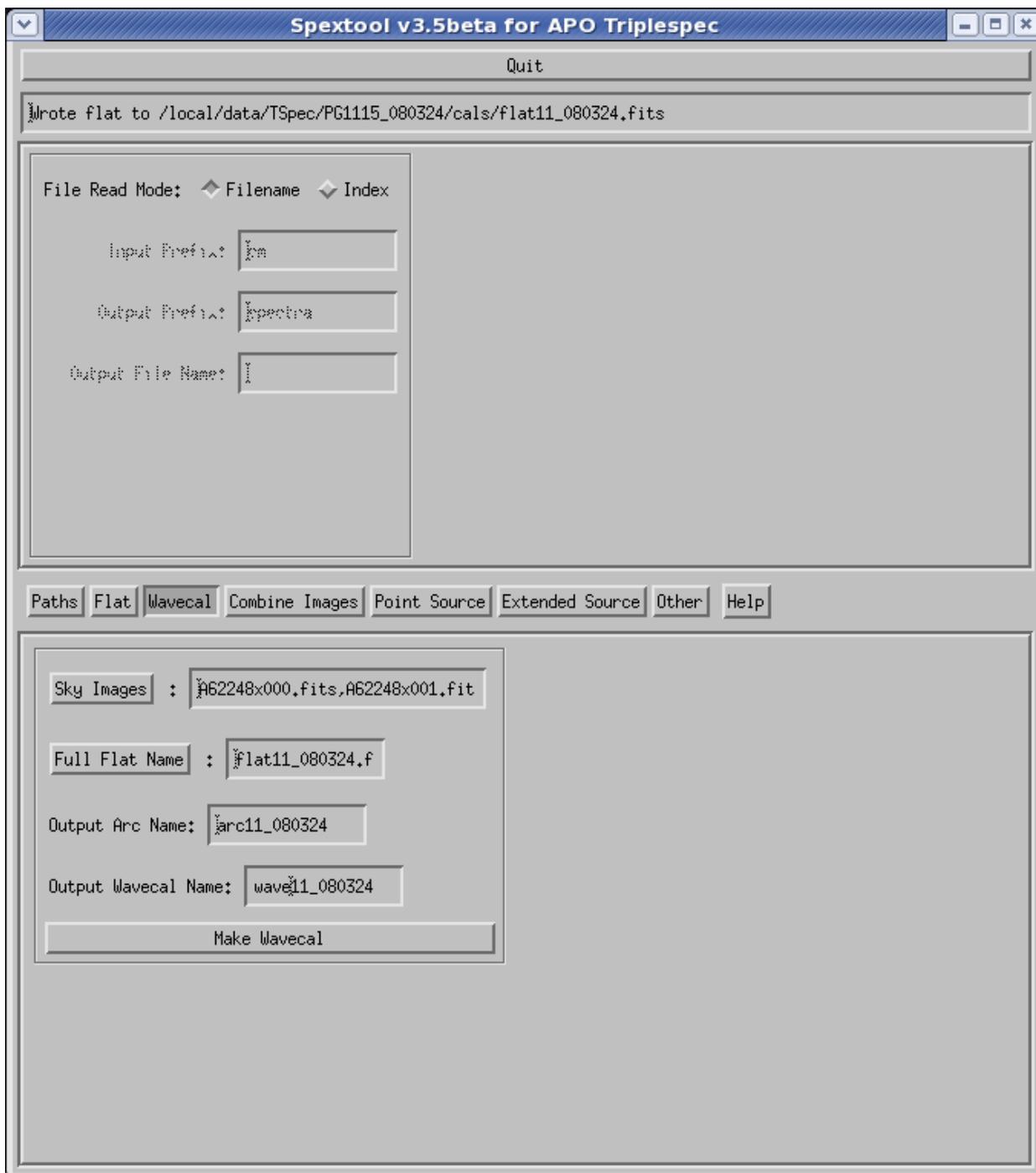- Select the flat field already generated for the appropriate night and slit.

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Figure 3: *Panel for creating wavecal files.*

- You may provide an output arc name (e.g., arc11-2008-05-09); however, this is not needed during the remainder of the reduction process.

- Provide an output wavecal name (e.g. wavecal11-2008-05-09)

- Click 'Make Wavecal.' The final wavelength calibration file is written to your cal directory.

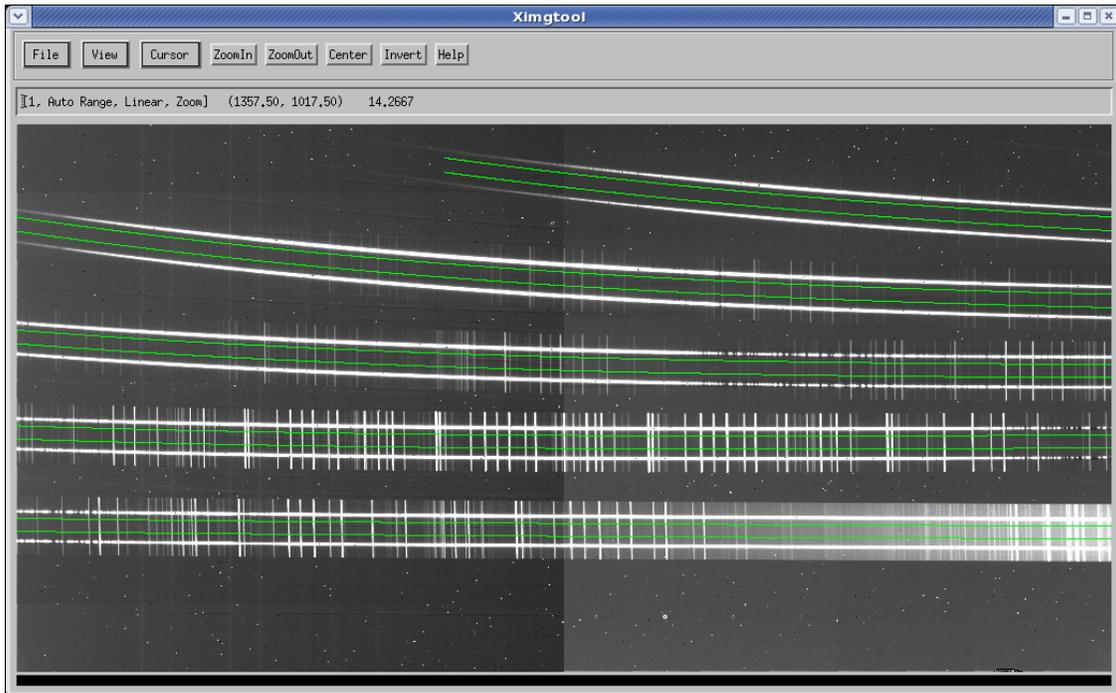- You should then see something similar to Figure figure4.

Figure 4: *Output displaying region over which OH lines were selected for wavelength calibration.*

8   Source Extraction

Now that the flat field and wavelength calibration files are created, they can be used to extract the object spectra. There are three basic technics for extraction: point source, extended source, and faint sources.

8.1   Point Source Extraction

Perhaps the most commonly extracted object types are point sources utilizing the two nod positions (A and B). For the most part, we assume that targets were observed using the nod script built into APO's Telescope User Interface, which observes at the different nod positions in the sequence ABBA.

8.1.1   Setup

- In the Main Base, click on the 'Point Source' button (Figure figure5).

- Choose the Reduction mode (A, A-B or A-Sky) based on the type of observations you have.

  - If you do not want to do any sky subtraction, choose 'A.'
  - **If you have paired nod observations, choose 'A-B' as your reduction mode.** This is the most common method. ALSO, if you would like to subtract off an individual sky image from a source image, you can use this mode. Note that in this case, after you create the Spatial Profiles, you will want to select 1 Aperture instead of 2.
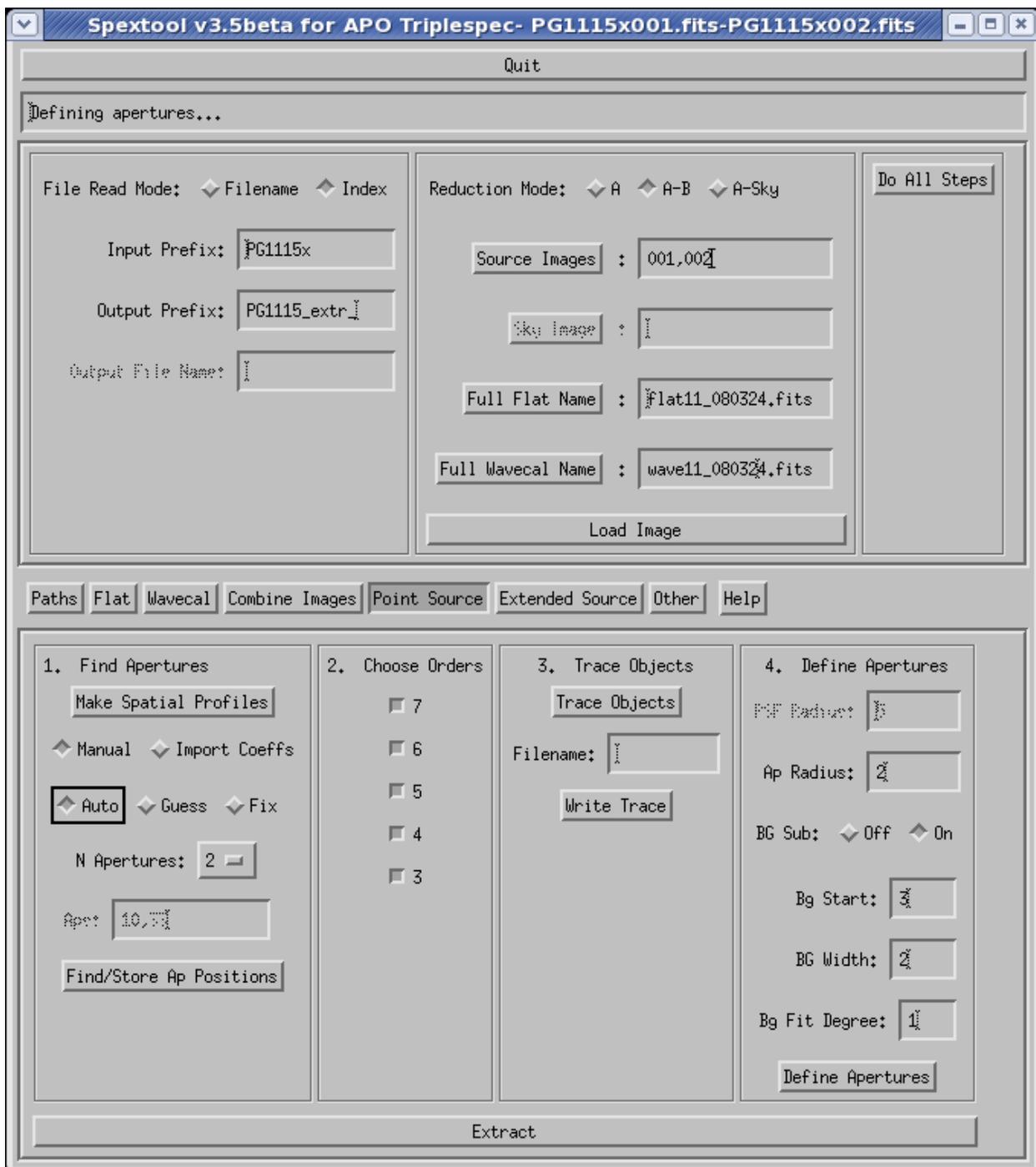
Figure 5: *Panel for creating wavecal files.*

○ **If there are individual sky images and you want to create a 'Super Sky Frame' to subtract from your on-source frames, use 'A-Sky,'** BUT first the Super Sky needs to be created.

– Making the Super Sky frame: If you 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 Main Base. Next to Beam Switching Mode, select 'A' since 'A-B' was designed for combining nodded faint objects. Click the 'Images' button and select the files you will use to make a sky frame (or select the 'Index' File Read Mode and enter the file name Input Prefix then type in the numbers of the files in the Images field). Turn on Background Subtraction and provide the full name of the flat field image made above (needed for finding the edges of the orders). Choose a statistic to combine the sky frames: a typical choice might be median. Give the full name of the output sky frame in the (e.g., targetname_sky) and click the Combine Images button. APOTripleSpecTool then scales and combines the sky frames, fixes bad pixels, and writes out the Super Sky frame.

• Assuming the A-B method, **select 'Index' under File Read Mode and enter your Input and Output Prefix. Type in the numbers of the first two object frames (e.g, 000,001 or 000-001; either notation is allowed), type or click in the names of the appropriate Flat Field and Wavecal files.** If you do not want to divide by the flat field, then turn off the flat fielding in the Other base. However, the flat field image is still required because its header contains information necessary for extraction process. If you do not want to wavelength calibrate the data, leave the Wavecal field empty. **Then click the Load Image button.** APOTripleSpecTool then subtracts the pair of images and divides the result by the normalized flat field. A 2-D image similar to Figure figure6 will be displayed, showing a positive and negative source.
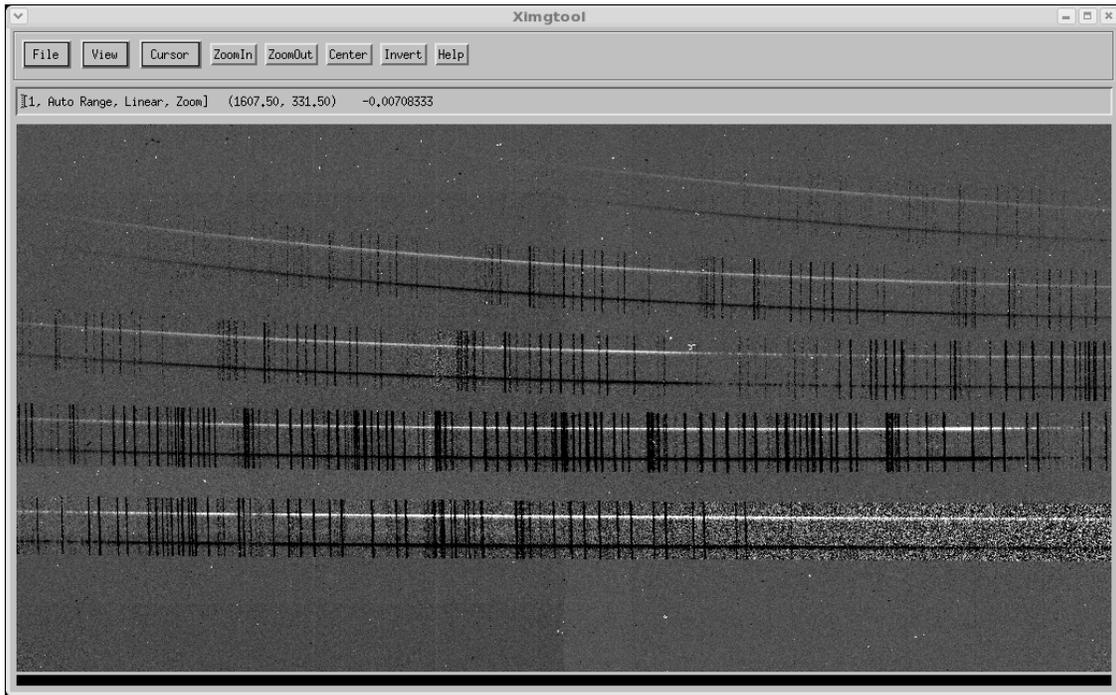

Figure 6: *The result of subtracting an image with a point source at one nod position from another image where the point source has been shifted to the other nod position.*

8.1.2 Find Apertures

- **In the Find Aperture Positions panel, 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 Spatial Profiles are displayed in a separate window (Figure figure7).

- If you wish to define extraction apertures based on the Spatial Profiles (which is normally the case), you should click on the Manual button. In some case, the you doe not want to specify apertures defined from the observed profiles, but rather may wish to extract spectra corresponding to apertures which have been previously defined based on observations of another object (e.g., a standard star). In this case, you 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 Section subsubsection8.1.3).

- **Under 'N Apertures', choose the number of apertures to be found (normally 2) automatically within the profiles and click the Auto button.** For typical spectra obtained in A-B mode,
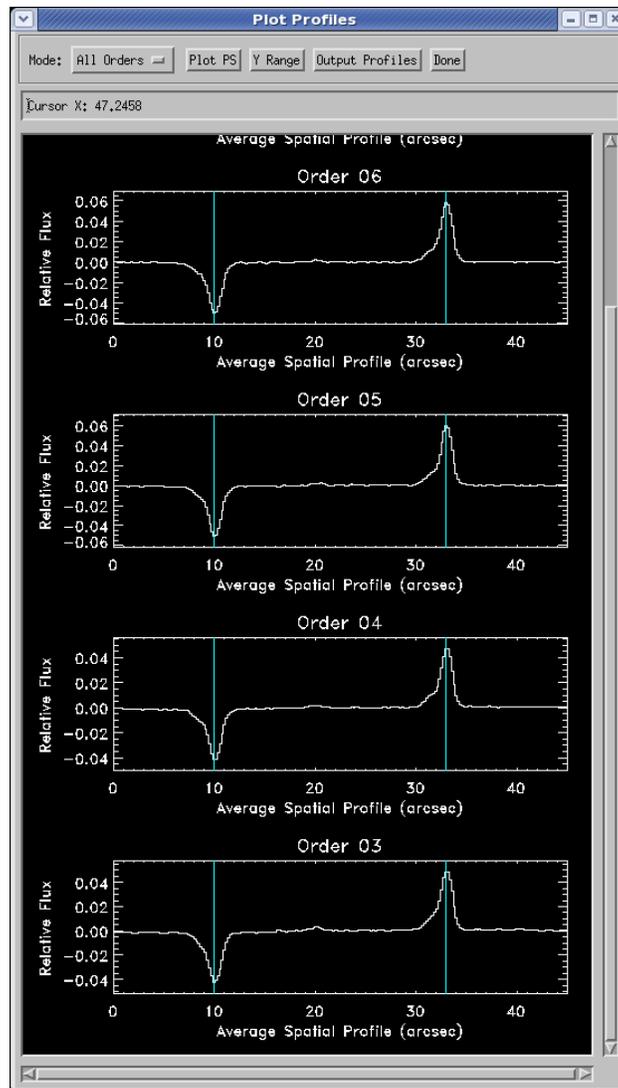

Figure 7: *Selection of aperture positions.*

there will be two apertures corresponding to the object in the A frame and its negative counterpart in the B frame. With the Auto button selected, **click on the Find/Store Ap Positions button** and APOTripleSpecTool will locate the centers of these profiles. If you have not taken spectra in A-B pair mode, select 1 for 'N Apertures' to be extracted.

- **If you have a faint point source for which only a noisy Spatial Profile can be constructed, the Guess or Fix Positions option can be chosen.** This would be particularly apparent in Order 07. The positions in ARCSECONDS along the slit for the centers of the extraction apertures should be given in the Aperture Positions field. If Guess is selected, APOTripleSpecTool will use these positions as initial guesses to locate the centers of the profiles. If Fix is selected, the entered positions will be used for the location of the apertures.

- **Choose the spectral orders to be extracted.** Normally the observer will want all spectral orders. However, if an order contains so little flux that the spectrum cannot be traced, you can de-select (un-click) that order.

8.1.3 Trace Sources

- **Click the 'Trace Objects' button** in the Trace Objects panel and APOTripleSpecTool will trace the centers of the apertures found above (Figure figure8). If you have not fixed the extraction apertures, APOTripleSpecTool 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 you have fixed the extraction aperture (e.g., for an extended source or a faint point source), APOTripleSpecTool will simply plot the specified positions on the image and use these as the traces.
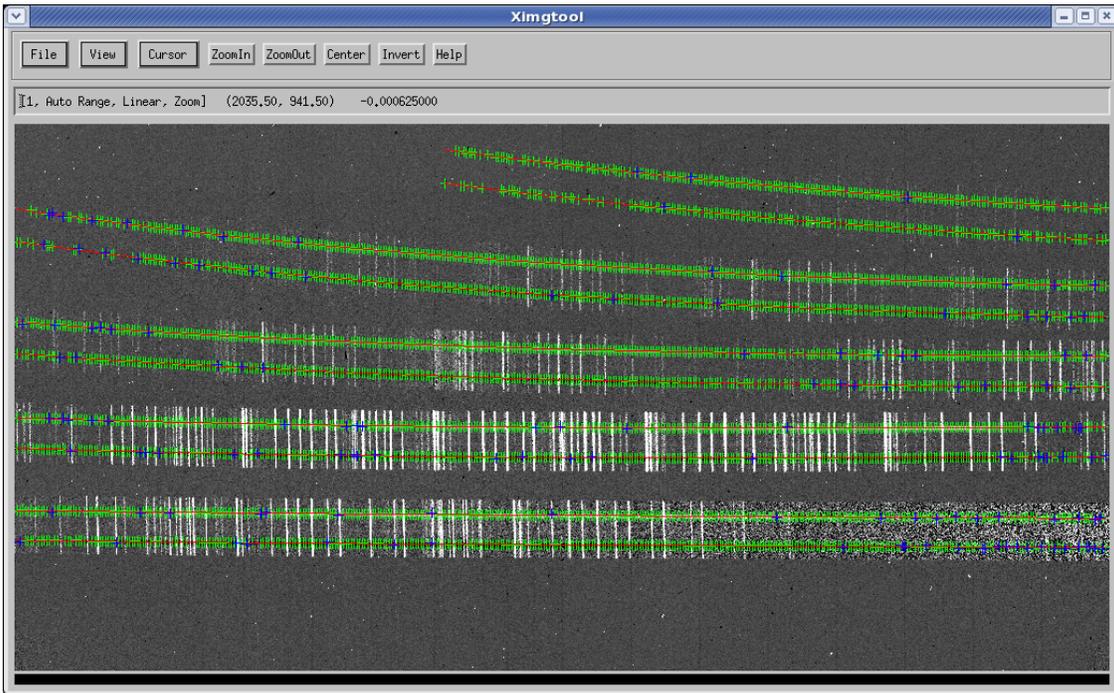

Figure 8: *Trace of source apertures.*

- 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, you should enter a file name for the output trace file (e.g., trace.dat) in the Filename field in the Trace

Objects panel and then click on the Write Trace button. The output file can then be used as described in the step above (Section subsubsection8.1.2).

8.1.4 Define Apertures

- The extraction apertures can now be defined in the Define Apertures panel. The PSF radius should not be set unless using optimal extraction, which has yet to be robustly tested as of v3.5beta.

- Choose the value of the radius of the extraction aperture (Ap Radius) in ARCSECONDS, based on the Spatial Profiles. The Aperture Radius is the size of the aperture, which Spextool will use to compute the source flux at each column. For non-optimal extraction, APOTripleSpecTool simply sums the source flux from the pixels within the Aperture Radius. **We have found that an Aperture Radius of about 2 seems to work best**, however, you should experiment with this value to find the best result for your objects.

- Choose whether or not to subtract local background. If background subtraction is desired, click the background subtraction button (BG Sub ON; on by default). **NOTE:** Due to the curved nature of the orders and the current method in which background is chosen, you must use precautions when choosing the slit positions to use as background. Since airglow lines are tilted with respect to the pixel columns used to determine local background, the airglow lines tend to increasingly contaminate the background as you move further from your source, thereby overestimating the background subtraction. Similarly, some regions of your spectra containing airglow lines that need to be removed will have underestimated backgrounds.

  We are currently in the process of updating the software to take into account this tilt. In the meantime, we suggest you select background that is relatively close to the source, similar to our suggestions in the next paragraph. Alternatively, you can apply a method developed by Adam Ginsburg at Colorado University, which uses IRAF to de-tilt and extract the orders (http://casa.colorado.edu/~ginsbura/APO_reduction_tspec.htm).

  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 Aperture Radius. Specify the degree of the polynomial used to fit the background in these windows and across the object aperture. Degree = 0 is a constant; Degree = 1 is a liner fit with slope and offset. **We have found that values of BG Start=3, BG Width=2, and BG Fit Degree=1 appear to work best**, however, the you should experiment with these values to find the best result for your object. **Now click the 'Define Apertures' button.** APOTripleSpecTool will show the apertures used for both the background (in red) and the object (in green) on the Spatial Profiles plot. The Aperture Radius value will be marked with a green vertical dashed line. APOTripleSpecTool will also draw the object apertures (in green) on the background-subtracted image (Figure figure9).

8.1.5 Extraction

- **The spectra will be extracted when you clicks on the 'Extract' button at the very bottom.** For non-optimal extraction, Spextool will fix known bad pixels within the extraction apertures in the pair-subtracted, flat-fielded image. It will then fit the background in each background window in each column and in each order, subtract the fit from each pixel in the aperture, and then compute the flux in the aperture. The flux at each column will be simply the sum of the flux values from all the pixels in the extraction aperture. Once it has finished extracting the object spectra, APOTripleSpecTool will apply the wavelength solution determined from the wavecal spectrum supplied.

- **After extraction, the wavelength-calibrated spectra for one of your observations will then be displayed in a widget called xvspec** (which can also be called separately by typing xvspec at the IDL command line; Figure figure10). The extraction aperture to be viewed can be selected from the Aperture pull down menu. Header information can be viewed by clicking on the Header button. Once the spectra are loaded, the ranges of the individual orders can be changed by clicking on the Modify Range button and then selecting an order from the Order pull down menu and entering Min
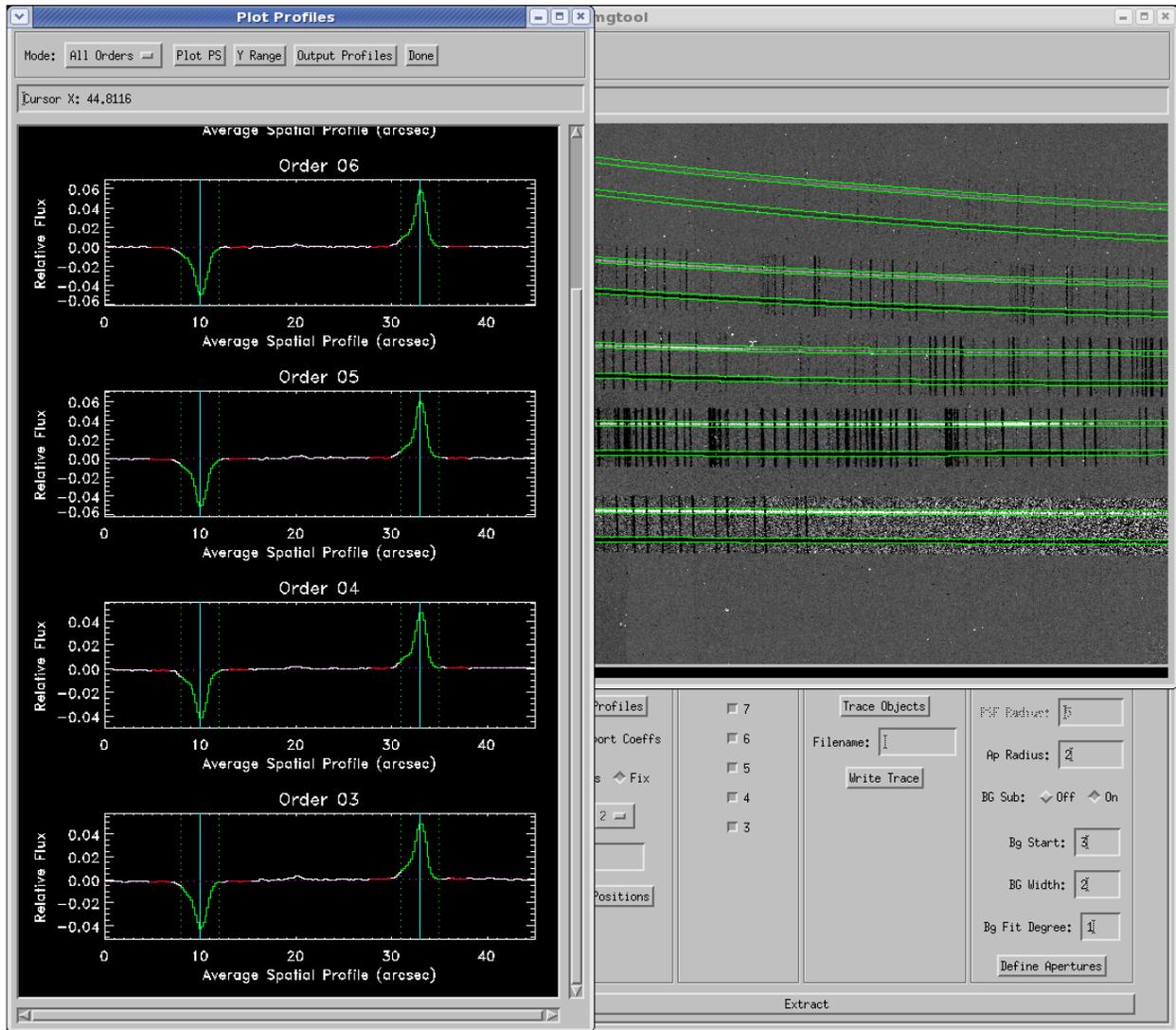
Figure 9: *Defining the aperture radius and background values.*

and Max values for the y axis of that order. The spectra can be smoothed with a Gaussian by clicking on the Gaussian Smooth button, and choosing the width of the smoothing kernel (in pixels) from the pull down menu. The color used to plot the spectra can also be selected by clicking on the Color button. A postscript file can also be written out by typing 'p' when the cursor is in the plot window. In addition, the error spectrum and signal-to-noise ratios can be displayed. To view a single order, click on the order with the left-most mouse button. A widget called xzoomplot will appear with the spectrum plotted. You can change the x and y range by hand using the fields at the bottom of the widget or interactively using the cursor. To learn about cursor commands type 'h' in the plot window.
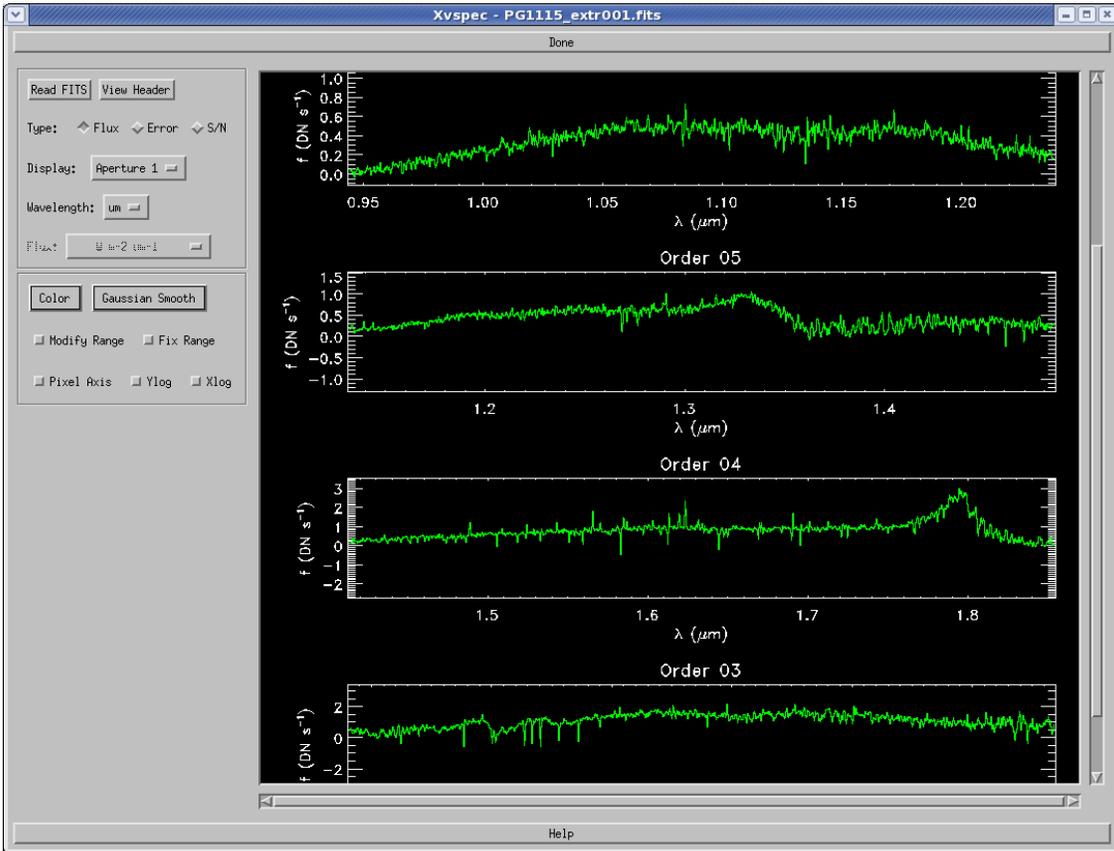

Figure 10: *Output extraction of each order for one observation.*

- Once the first pair of object spectra has been extracted and you are happy with the extraction parameters, **the full list of file numbers for the rest of the files in an observing set can be inserted in the Source Images field in the Reduction Mode panel** (e.g., 002-007 which is equivalent to 002, 003, 004, 005, 006, 007). This assumes that each pair of files contains two nod positions using the nod script in TUI (ABBA). **All of these images will then be reduced automatically by clicking on the 'Do All Steps' button** in the panel to the right of the Reduction Mode panel.

8.2   Extended Source Extraction

This section has yet to be thoroughly tested. If you find a discrepancy or bug, please let us know. Here, we assume that Extended Sources will have corresponding sky background images.

- The first main difference with extended objects is that you cannot select an option to Auto find or Guess the Aperture Positions. You must enter these manually. The positions in ARCSECONDS along the slit of each aperture to be extracted can be entered in the Positions field. Click on the Store

Ap Positions button and APOTripleSpecTool will locate the specified positions. Note that 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. You should keep this in mind when specifying aperture positions in the Extended Source mode.

- The next major difference comes about under the Define Aperture panel. The radii of each defined aperture must be entered in the Ap Radius field (e.g., 1.5,1.5 for 2 apertures) and should be separated by commas. The positions, in arcseconds along the slit, of the background windows must also be specified. An example might be 0-2, 13-15. Note that differential atmospheric refraction will cause peaks to be located at slightly different positions along the slit. You 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.

- Click the Extract button and continue as normal.

8.3 Faint Source Extraction

If APOTripleSpecTool has difficulty tracing the object of a single, A-B, or background-subtracted spectrum, then you may want to consider first combining the images and then extracting the spectrum from the final coadded image. **If your objects are not in the same positions in the slit, then this method might produce a final image with multiple peaks, which may provide difficulties during extraction.**

- **Move to the Combine Base** by clicking on the 'Combine Images' button in the middle of the Main Base. If the data were acquired by moving the object between two positions on the slit (the pair method), choose A-B; if not, choose A. If you are selecting the A-B method, then a button will appear that sorts ABBA groups into ABAB. If your data was taken in ABBA pairs, then click on this button. Otherwise, if your data was observed in an ABAB nod sequence, make sure this button is NOT checked.

- With Index selected under File Read Mode (along with desired Input Prefix), **type the image numbers into the Image field (e.g., 000-007). Turn on Background Subtraction and enter the full name of the final flat field image in the Full Flat Name field. Choose the desired statistic for combining the images (a typical choice might be Median).** Note that a weighted mean may not be an appropriate statistic because the assumptions underlying the weighted mean as the best estimate of the mean may not be satisfied due to guiding error and slit losses. This effect is most pronounced in short integration exposures. If Mean is chosen then the error of the final combined image is computed as sigma mu = sigma/sqrt(N). If a median is chosen, then the error on the median is computed as sigma med = MAD/sqrt(N) where the MAD (Median Absolute Deviation)=1.482*median(datamedian). The constant 1.482 is set so the MAD = sigma for a Gaussian distribution.

- Finally, provide the full name of the output file in the Output Name field (e.g., spec376-381.fits) and click on the Combine Images button. APOTripleSpecTool will then combine the images and write the result to the proc directory.

- The combined image may now be extracted by defining the Data Path in the Path Base to be the proc directory. The file read mode should then be set to Filename and the reduction mode set to A. You can then proceed as normal. APOTripleSpecTool will write both beams (apertures) to a single file. They can be combined in xcombspec by choosing the Combine Apertures options.

9 Combine Spectra

Xcombspec allows you to combine individual spectra extracted with xspextool into a single output spectrum. Xcombspec will combine the individual spectra after optionally scaling all of them to a selected level. The

purpose of combining spectra is to increase the S/N of the source spectrum by averaging out the fluctuations due to noise.

As a result of guiding errors, variable sky transmission, etc., rarely will it be the case that all of the individual spectra have the same flux level. Directly combining such 'raw' spectra, with their different flux levels can defeat the purpose of the combining process, by increasing, rather than decreasing, the noise. Furthermore, one clearly does not want to discard most of the spectra. Scaling the spectra to a common flux level will allow you to make use of the entire data set.

9.1 Setup

- Start the GUI by typing 'xcombspec' into the IDL prompt.

- Choose the input mode for the file names.

  ○ If the you wish to combine several spectral files located in various directories, you should create a separate text file listing the full path names and filenames of these spectra, and then choose the 'Text File' input mode. The filename of the text file can then be input into the 'File Name' field, or selected from the list presented when the 'File Name' button is clicked.

  ○ If 'Manual' mode (the default) is chosen, you must enter the directory path where the data files reside in the 'Path' field, or click on the 'Path' button and choose the path from the list shown. If xcombspec is started up in the directory containing the data files, no Path name is required. You 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., rspec10.fits, rspec11.fits, rspec12.fits, etc.), then you should choose 'Index' mode (the default). The input prefix must be typed into the 'Input Prefix' field (e.g. rspec), and the file numbers entered into the 'Files' field (e.g., 10-20). If the files have different prefixes, you should choose the 'Filename' mode, and specify the file names in the 'Files' 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 input files contain spectra from multiple apertures that are to be combined, you should select the 'Yes' button next to the 'Combine Apertures' label. Multiple aperture data in a single spectral file would be generated if, for example, a faint point source were observed in A-B mode and the individual two-dimensional data image files were combined before the spectra were extracted. If the data files consist of observations of a single point source, observed in A-B mode and extracted individually, the input files should not contain multiple apertures.

- **Click 'Load Spectra.'** The spectra and their orders will then be displayed in the display panel on the right hand side. You have the choice of displaying the fluxes, the errors, or the S/N ratios as a function of wavelength, by choosing from the 'Type' pull-down menu in the upper right hand corner of 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.

9.2 Modifying Spectra

- If you wish to scale the spectra, you should **select 'Scale' from the pull down menu under the 'Modify Spectra' section, and choose an order from which the scaling should be determined**. Xcombspec determines a single scale factor to be applied to all orders of a given spectrum. Therefore, we suggest that the scale factors should generally be determined from the middle orders, unless there is a particular reason for choosing another order. We also recommend choosing an order with a high overall S/N value. Once the order is chosen, the Xscalespec plot window will appear.

- You should then choose a wavelength range to be used for determining the scaling factors. It is usually best to select the range with the highest count rate. **Type 's' and click with the left most mouse button to specify the short wavelength limit of the selected range. Click again with the left most button to specify the long wavelength limit.** Dashed blue vertical lines will show the designated wavelength range. You can also zoom in on any region with the 'z' command.

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- Choose the type of scaling to be done from the pull down menu next to the 'Scale to' label. You can choose no scaling ('None'), scale all spectra to the median of the plotted spectra ('Median'), or scale to the level of a particular reference spectrum ('Spectrum') over the selected wavelength range. If 'Spectrum' is selected, the number of the desired reference spectrum should be chosen from the pull down menu next to the 'Spectrum' button. Xcombspec will then scale each spectrum by the appropriate amount. You can inspect the result with the zoom commands, change the axis limits of the plot, re-select new reference spectra or scaling wavelength ranges, etc. If 'None' is chosen at any point in this process, the original unscaled spectra will be re-plotted. **For most cases, we recommend using the Median for the scaling.** However, if you observed on a night with intermittent clouds or lost flux significant flux due to slit loss, it may be advisable to select the observation with the highest flux to obtain the best absolute flux calibration.

- Once you are satisfied with the scaling, **click the 'Accept' button** (Figure figure11). If the results are not acceptable, the scaling can be redone by choosing a new scaling order, a new reference spectrum, a different wavelength range; or the spectra can be reloaded and the process repeated from the beginning.

Figure 11: *Result after scaling spectra.*
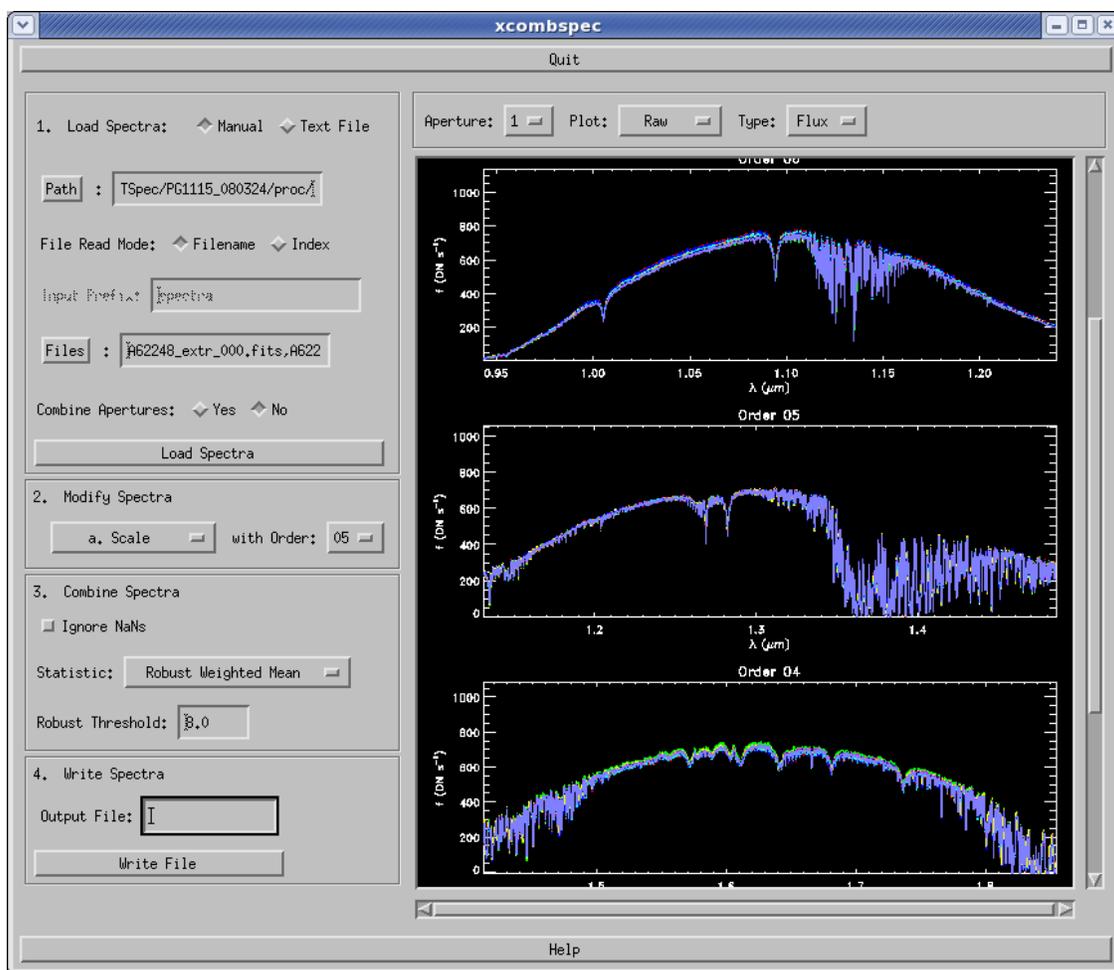
- At any point before or after scaling, you may exclude a particular spectrum from the combining procedure by choosing the 'Remove' option from the pull down menu in the 'Modify Spectra' box. Select an order to pull up the XSelectspec plot window and exclude a particular spectrum from by unchecking its corresponding box number on the left hand side. By hitting the 'Accept' button,

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Xcombspec will remove the selected spectra from all order and further procedures in the combing process. If scaling had already been applied, then you may need to recompute the scaling with the new set of spectra.

- Ideally, all of the spectra should now lie perfectly on top of one another. However, we have found that this is sometimes 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 reference spectrum, implying that the spectral slope is varying from one spectrum to another over the various orders. This slope change may be the result of guiding errors, atmospheric dispersion, and time-variable, wavelength-dependent changes in seeing rather than a procedure involved in the data reduction. You can reduce these discrepancies and increase the S/N of the final combined spectrum by correcting for the slope variations. **Click on 'Correct Spectral Shape' in the pull-down list under 'Modify Spectra.'** All of the spectra in a given order should lie on top of one another. WARNING: Use this option with caution as it can sometimes generate obviously spurious results, particularly for low S/N data. NOTE: This process cannot be undone without reloading all of the spectra and starting from the beginning.

9.3   Combining Spectra and Writing File

- You should now choose the statistic to be used for the combining procedure. There are several statistics to choose from. For the robust statistics, a clipping threshold can be chosen. We recommend using the 'Robust Weighted Mean' with Threshold=8.0, which is the default.

- Next, you should choose the name of the output file in the 'Output File' field and click the 'Write File' button. The final combined spectrum will be displayed in xvspec.

10   Telluric Corrections

Molecules such as water, oxygen, and OH in the Earth's atmosphere absorb and emit light at specific wavelengths, producing bothersome telluric contamination lines in ground-based observations. In order to remove these lines from our spectra, a correction function must be prepared by comparing a high resolution model of a standard star to observations of at an airmass similar to your science targets. The resulting function can then be applied to observations of your science target in order to remove the contaminating telluric features.

10.1   Basic Telluric Correction

The xtellcor_basic GUI simply divides an object spectrum by some standard star spectrum (not necessarily an A0V), and then you can choose to multiply the result by a blackbody. This is intended as a quick calibration method.

- Start the GUI by typing 'xtellcor_basic' in the IDL prompt.

- If you are not working in the directory where the data is stored, enter the path either by clicking on the Path button or by typing the path into the field, otherwise, you may leave this field blank. Enter the appropriate filenames of the combined standard star and combined science target in the 'Std Spectra' field and the 'Obj Spectra' field, respectively. Alternatively, you may **click on the corresponding buttons and select your standard and object files**.

- Next, you should determine if there are residual wavelength shifts between the standard star and your object that could induce spurious noise and artifacts during the telluric correction process. **Choose an order form the pull-down menu 'Order' under the 'Determine Shift' section, then click the 'Get Shift' button.** The Xfindshift panel will appear with both the object and telluric spectrum plotted in the upper window and the resulting correction plotted in the bottom panel.

  ○ **Select a region containing relatively strong atmospheric features by typing 's' and clicking the left mouse button on either side of the desired region.** HINT: Try to select a

region with relatively low noise. Also, points that fall below 0 flux can confuse the search routine, so avoid these regions as much as possible.

- ○ **Click the 'Auto Find' button**. This will shift the telluric spectrum by fractions of a pixel and search for the best value, corresponding to the minimum RMS in the selected region.

- ○ If you would like to try a different region, hit 's' to select a new wavelength range. You can manually set the shift field to 0 to reset the search.

- ○ To use a different order, click cancel and select another order to restart the shift-finding process. Xtellcor_basic uses a single shift value for all orders, so it is recommended that you choose the order with the highest S/N in a region containing telluric features. Xtellcor, on the other hand, generates and stores independent shifts for each order.

- ○ When you are satisfied with the shift you have found, **click on the 'Accept' button** at the bottom of the panel to apply the shift to ALL orders.

- In order to restore the continuum shape and preserve the absolute flux level of the object spectrum, select the 'Yes' button (selected by default) next to the 'Restore Coninuum' label. Then, input the blackbody temperature and the V magnitude for the standard star and choose units for the output spectrum (usually W m^{-2} μm^{-1} or Jy is good for IR).

- Give a name in the output field and click 'Construct Corrected Spectra.' The corrected spectrum will be written to the specified input path.

10.2   A0V Standard Star

Xtellcor uses an A0 V standard star along with a high-resolution model of Vega to remove the intrinsic stellar features and perform telluric corrections on the result. A comprehensive description of this procedure can be found in the paper by Vacca, Cushing, & Rayner (2003, PASP, 115, 389), which should be referenced during publication of the data.

10.2.1   Setup

- Start the GUI by typing 'xtellcor' into the IDL prompt.

- Input the combined spectrum you created for your A0V standard star. Then type in the B and V magnitudes for your A0V standard. Then input the combined spectrum you created for your science target. Click 'Load Spectra'. Note that the Airmass values for both spectra, and the airmass difference, will appear at the top of the Xtellcor panel.

10.2.2   Construct Convolution Kernel

The next step involves generating a convolution kernel that will be applied to a 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 appropriate resolution. 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. For TripleSpec, the Deconvolution method is recommended and is described below.

- **Make sure the 'Deconvolution' button is selected and choose an order**. 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. We have found Order 06 to be best for this option.

- Click the 'Construct Kernel' button. The Xconkern panel will appear and the spectrum of the A0 V star in the chosen order will be plotted in the upper half.

- You can press the 'z' keyboard button to zoom to the region of interest and better fit the continuum.

- **Press the 'n' keyboard button to select regions of the continuum** to fit a polynomial and to be normalized. The best regions are those free of atmospheric absorption lines that flank the Hydrogen line were fitting. The regions selected are marked in dashed blue lines

- Select a Fit degree (anywhere between 7 and 12 appears to work best).

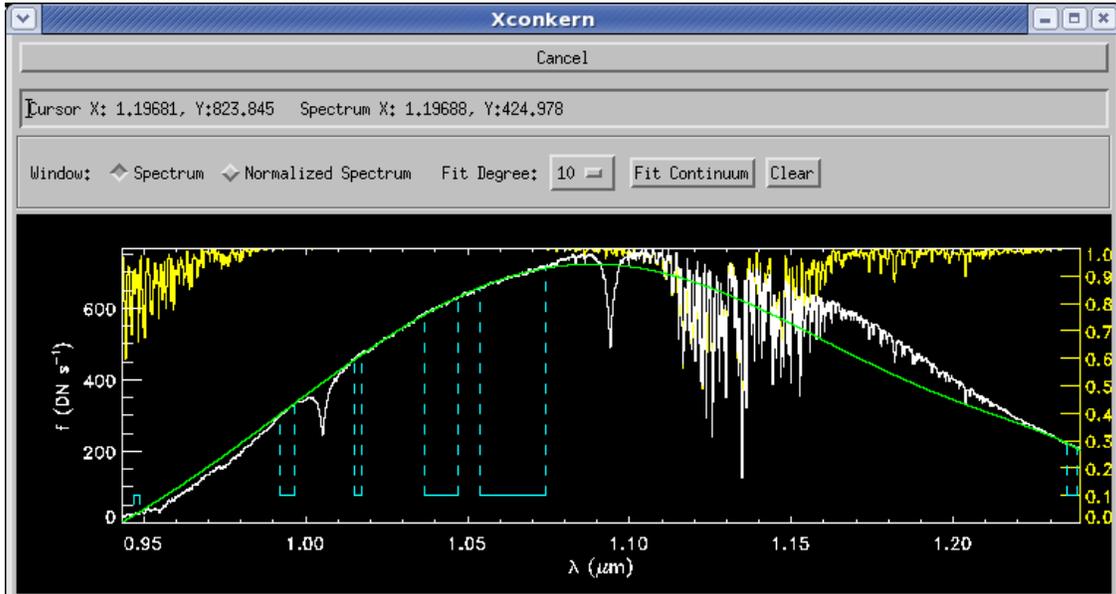- Click on Fit Continuum. A green curve will then appear (Figure figure12).

Figure 12: *Fitting a continuum to an A0V standard star (Order 06).*

- You may modify your selections by pressing the 'm' keyboard button, and adjusting the region selected in blue, or by pressing the 'Clear' button to start over.

- Repeat the above steps until you obtain a desirable fit. It could help to select a small region at both end of the order, to serve as anchors for the curve

- Once you have obtained a satisfactory continuum, choose the Normalized Spectrum button, which removes the continuum around the desired Hydrogen line.

- By pressing 's', select a region within the Hydrogen line to fit. You should experiment with narrow and wide ranges to find the best possible fit.

- **Click on the 'Construct Kernel' button.** The program generates a convolution kernel that is convolved with the model spectrum of Vega. The convolved spectrum of Vega is then divided into the observed spectrum of the standard A0 V star. A colored graph should then appear in the lower window that provides a fit the A0V Hydrogen line with that of Vega (Figure figure13). This plot shows the observed spectrum of the standard star, the original Vega spectrum (binned to the sampling of your standard), the convolved Vega spectrum, and the result of the division (residuals).

- Repeat until you obtain a decent fit. A good fit should have a Max Deviation of <1.5 and an RMS Deviation of <0.7.

- Once you are satisfied with the residuals, click the 'Accept' button.
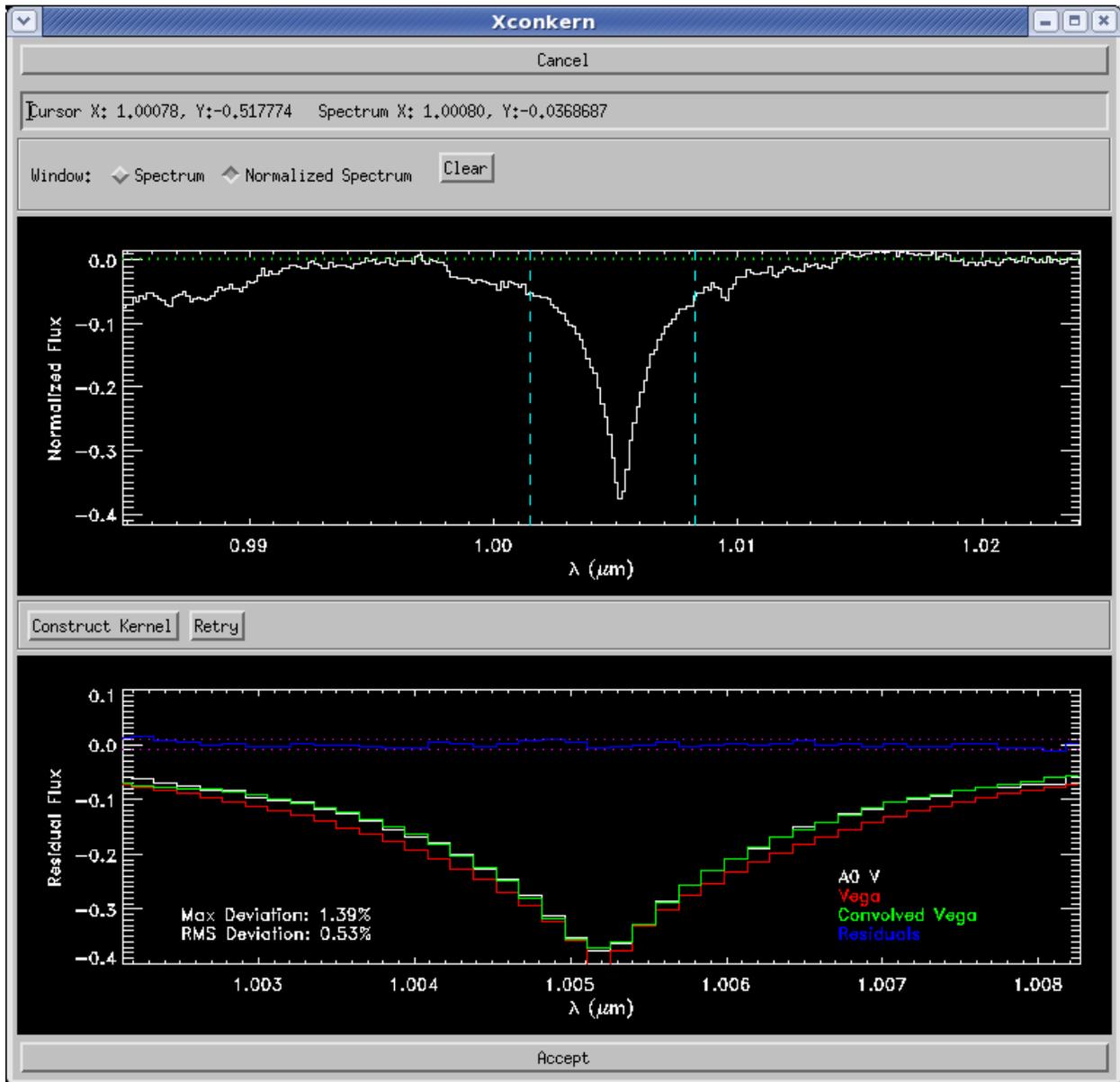
Figure 13: *Fitting the Hydrogen line of the A0 V standard star.*

10.2.3   Scaling Lines

This step will allow you to 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' button. The Xscalelines panel will appear.

- **Normally, we have found that it should be acceptable to simply accept the defaults**, but if find small residual Hydrogen lines in your final spectrum, then you can try your hand at this procedure.

- In the bottom window of the panel is the estimate of the telluric spectrum (in white) and a typical atmospheric absorption spectrum (in yellow). The Hydrogen lines present in A0 V stars are labeled and marked in green. Ideally, the telluric spectrum should look like the typical atmospheric absorption spectrum times the instrument throughput (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. For TripleSpec data, all scales are set to unity.

- In the middle of the base, you can **choose which order you would like to start with**. At the top of the widget you can input a different 'vshift' until your Hydrogen line looks fairly symmetric. Values as large as 300 km/s are not uncommon.

- Next, you will want to scale the lines in each of the orders such that basically the yellow spectrum and the white spectrum match. **The scale factors can 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.** When you release the button, xscalelines will re-compute the new telluric spectrum with the new scale factor array. The typical telluric spectrum shown in yellow should give an idea of where the true atmospheric features are and what their approximate relative strengths should be after removal of the stellar H lines. The telluric-corrected object spectrum can be examined at any stage by selecting the 'Object' button at the top of the lower window.

- In regions where the line is fairly well defined, **you can use the key 'e' to estimate the scale factors needed to match the spectra.** To use this, type 'e' and then click your left mouse button on either side of the line you are trying to scale. WARNING: Use of the 'e' key has been known to crash xtellcor under certain circumstances.

- If at the end of this process, the H line has not completely been removed from the telluric correction spectrum, you have 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 fix) 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. To undo the interpolation, type 'u'. NOTE: This feature should be used with caution since any atmospheric features present will also be removed from the telluric correction spectrum.

- When you are satisfied with the telluric spectrum in each order, click on the 'Accept' button.

- Select the desired units for the output telluric-corrected object spectrum from the 'Units' pull-down menu (such as W m^{-2} μm^{-1} or Jy). Then click on the 'Construct Telluric Spectrum' button. The program will then construct the telluric spectrum for each order.

10.2.4 Residual Wavelength shift

This step determines residual wavelength shifts that may exist 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.

- To estimate the wavelength shifts and correct them, **choose an order from the Order pull-down menu** under 'Determine Shift' of the Xtellcor control panel. **Then click on the 'Get Shift' button.** The Xfindshift panel will appear.

- The object spectrum and the telluric spectrum are both plotted in the upper window. The result of dividing one by the other is shown in the bottom window.

- Select a region containing reasonably strong atmospheric features in both spectra by typing 's' (for 'select') and clicking with the left mouse button on either side of the feature. **HINT: Try to select a region with relatively low noise.** Also, points that fall below 0 flux can confuse the search routine, so avoid these regions as much as possible.

- **Then click the 'Auto Find' button.** 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.

- The wavelength shifts can be reset to zero by typing '0' in the Shift field and hitting return.

- If you wish to check the shift obtained from a different region, type 's' and select a new wavelength region. To determine the shift estimated from other orders, click on the 'Cancel' button, choose a new order from the Xtellcor control panel, and repeat the procedure.

- When you are satisfied with the shift found by Xfindshift, click on the 'Accept' button at the bottom of the panel. This shift will be applied to this order.

- You can then repeat the process for the rest of the orders.

10.2.5 Writing File

Finally, give the name of the output file in the 'Object File' field. You 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.

10.3 Existing Telluric Spectrum

If you have observed one A0V standard with which to perform telluric corrections for several target stars, it is possible to just run xtellcor for the first target and then use the output telluric correction spectrum for the rest of your targets.

- Start the GUI by typing 'xtellcor_finish' in the IDL prompt.

- If you did not start xtellcor_finish from the directory containing your object and telluric spectra, then type the input path, or click the 'Path' button to select the appropriate directory from the list.

- Input the name of the file containing the object that you wish to correct, or click the 'Obj Spectra' button and select the file from the list.

- Input the telluric correction spectrum generated from your standard star ('_tellspec.fits').

- Proceed with 'Get Shift' as you did with xtellcor above.

- Provide a name for the output file in the 'Object File' field and click the 'Correct Spectrum' button.

11 Merging Orders

Use this procedure to merge the various orders of a telluric-corrected spectra into a single spectrum.

- Start the GUI by typing 'xmergeordrs' in the IDL prompt.

- Type in the file name of the data, or click the 'Spectra' button to choose the combined, telluric-corrected spectrum for which you want to merge the orders.

- Make sure 'Weighted Mean' is selected and click 'Load Spectra.'

- **Choose an 'Anchor Order' from the pull down menu.** The Anchor order is the order with which Xmergeorders will start, usually the first order (Order 03). All other orders will be added to this order (with appropriate scaling factors applied, if desired). Thus, the anchor order will never scale and sets a base for determining the scaling of the other orders.

- After choosing an Anchor order, you will be presented with a list of of neighboring orders that can be merged. **Select the order you wish to add.** The anchor order and the order to be added will both be plotted in the upper plot window next to the control panel for Xmergeorders. 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. In order to match and merge the two spectra, there are two main things you need to do: scale them, then combine them.

- In order to scale them, zoom in on the region of overlap (type 'z' and then click your mouse in opposite corners of the region you wish to zoom). Then, type 's' and then click with the mouse to the left and to the right of the overlapping region you wish to use to determine a scale factor. Dotted red lines appear in the points, which you select. Click the 'Auto Scale' button. Repeat until you are happy with the scaling. **Generally, we have found that scaling for TripleSpec data has not been necessary, and that the orders are ready to combine.**

- You can also trim each of the orders so you get the best possible match (take a look at the box showing S/N while you do this – it will show you where you have the best sensitivity for each spectrum). In order to trim, toggle on 'green' or 'blue' to select which order and either 'left' or 'right' depending on which side youd like to trim. Make sure the 'Overlap' radio button is selected above the upper plot. You may then specify the trimming limits by clicking on the upper plot. In order to undo something youve trimmed, use 'u.'

- **Next, click the 'Combine' radio button** above the window displaying the merged spectrum to preview what will be produced. (Figure figure14).

- When you are satisfied with the scaling and trimming, **click the 'Merge Orders' button**. The orders will then be combined using a weighted average.

- Select the next order to Add and repeat the steps for scaling and trimming until you are finished.

- Type in the desired output name and his the 'Write File' button

12 Additional Tools

- Xcleanspec is a tool to clean the output spectrum, by removing noisy sections. It also allows you to smooth the spectrum. Another nice feature of this program is that you can overplot on top of your spectrum the atmosphere as well as the hydrogen lines.

- Xsmoothspec is used to smooth the output spectrum.

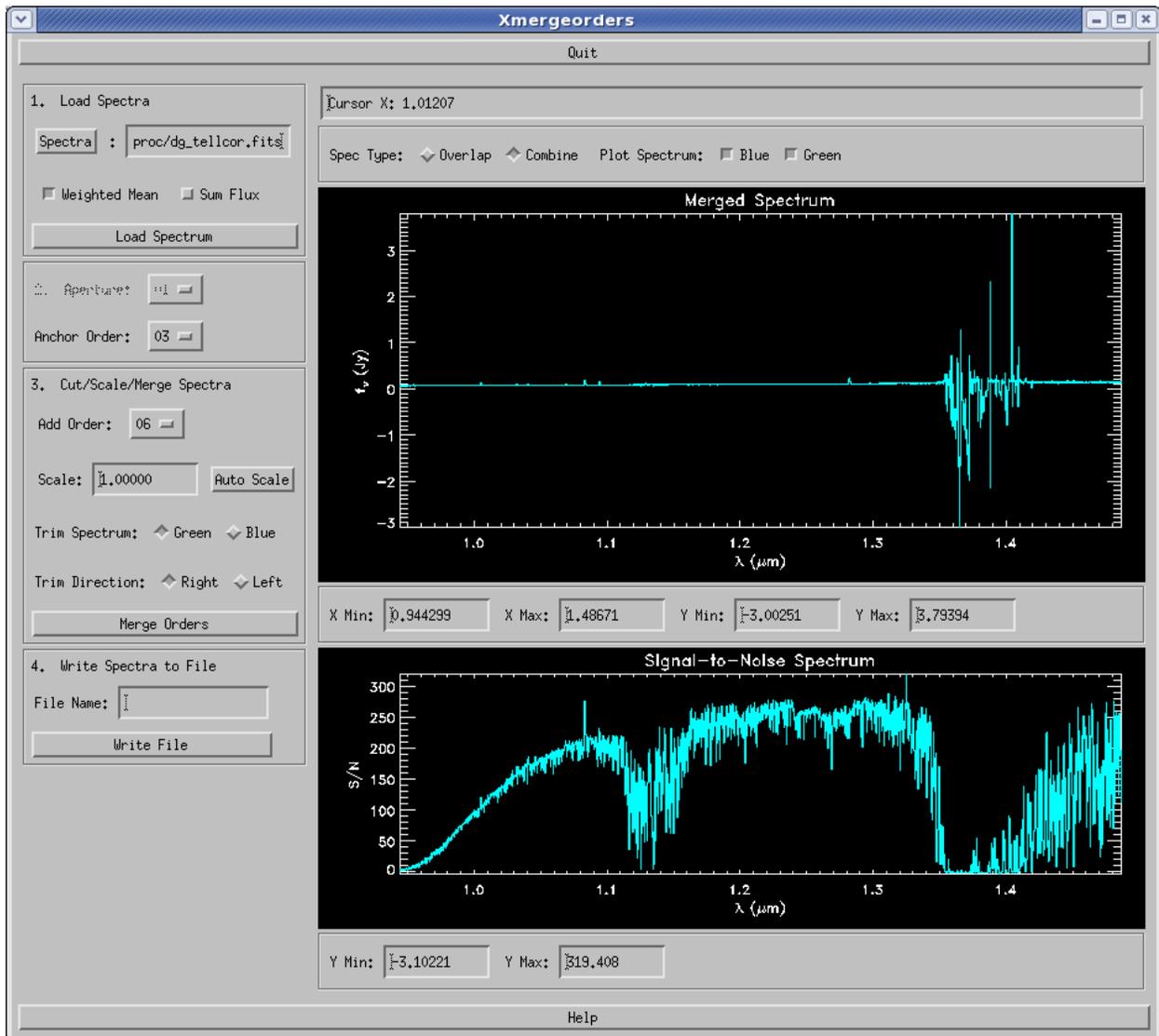- Xvspec displays spectra extracted using Spextool.

Figure 14: *Merging orders to produce the final output spectrum.*

13   References

This document is mostly intended as a recipe for using APOTripleSpecTool, so all algorithms used are not necessarily explained. When this document does not address those types of questions, refer to the Spextool helpfiles (Spextool2/helpfiles/) for a more complete description (additionally, there is an extensive description of various keystrokes used within the GUIs).

- Spextool: http://adsabs.harvard.edu/abs/2004PASP..116..362C

- Telluric Correction (using xtellcor.pro): http://adsabs.harvard.edu/abs/2003PASP..115..389V

- SpeX: http://adsabs.harvard.edu/abs/2003PASP..115..362R

14   Revision History

- **2009-07-16**

  - Release of updated APOTripleSpecTool providing bug fix under the Combine Images base in xspextool.
  - Update procedure for combining sources during faint source extraction (Section subsection8.3)

- **2009-05-01**

  - Added a paragraph describing the location and format of the bad pixel mask (Section section5).
  - Included a method for mitigating the issues involved with the order curvature and spectral line tilts, which can be accomplished during aperture and background selection of the extraction procedure (Section subsubsection8.1.4).
  - A link to alternative data reduction routines by Adam Ginsburg at the University of Colorado has also been included for detilting of spectral lines (Section subsubsection8.1.4).